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TENNESSEE VALLEY AUTHORITY

CHEMICAL ENGINEERING REPORT NO. 9

CORROSION TESTS
OF METALS
AND CERAMICS

BY
THE STAFF OF THE
DIVISION OF CHEMICAL ENGINEERING

THIS REPORT COMPILED BY
L. D. YATES

WILSON DAM, ALABAMA
1951

TENNESSEE VALLEY AUTHORITY
WILSON DAM, ALABAMA

DIVISION OF CHEMICAL ENGINEERING,
October 11, 1950.

Mr. NEIL BASS,
*Chief Conservation Engineer,
Tennessee Valley Authority,
Knoxville, Tenn.*

DEAR MR. BASS: It is with pleasure that I forward, with request for publication as a public document, the attached report entitled "Corrosion Tests of Metals and Ceramics." This is Report No. 9 in the Chemical Engineering Series being prepared by members of the division, and it was compiled by Mr. L. D. Yates, chemical engineer.

Very truly yours,

CHARLES H. YOUNG,
Director of Chemical Engineering.

Preface

This is Report No. 9 in a series of publications that describes the chemical engineering activities of the Tennessee Valley Authority, and it presents the results of some of the corrosion tests that were made as necessary parts of the various experimental programs that have been undertaken. The Division of Chemical Engineering of the TVA has been concerned with the development, through the laboratory, pilot plant, and plant phases, of processes for the production of fertilizers and for the utilization of natural resources of the Tennessee Valley. In each of these steps in development, problems for which no solution could be found in the literature have been encountered in the selection of materials of construction to withstand the corrosive action of the materials being processed. Corrosion testing has been used as a means in the solving of these problems. Although some of the results that have been obtained have been published in technical journals, the present report serves to bring together in one compilation those of the corrosion test results that might be of interest to others outside TVA. Other reports in this series covering the development of processes present information on the materials of construction used in the plants and describe operating experience with these materials.

The compiler of this report has been responsible for carrying out only a few of the tests for which results are reported, and it would be virtually impossible to give a complete list of those who contributed to the accumulation of test data. A. W. Beinlich and G. L. Crow carried out a large part of the work and contributed to the report in an outstanding manner by assembling data and by preparing parts of the manuscript. The following members and former members of the TVA staff also contributed significantly to the work: J. C. Barber, H. A. Bennett, W. J. Darby, A. B. Harrison, A. Hendrix, H. S. Jerabek, J. S. Lewis, R. R. Ludlum, D. J. Mack, Mary H. Malone, J. A. McCollum, L. I. Mitchell, G. R. Pole, G. C. Robinson, D. E. Rosson, E. P. Tait, and M. L. Taylor. Julius Silverberg and H. J. Kerr were of considerable assistance through suggestions regarding content and arrangement of tables and in the preparation of the manuscript.

The following TVA chemical engineering reports may be obtained from the Superintendent of Documents, United States Government Printing Office, Washington, D. C. Other reports in the series are in preparation.

General Outline of Chemical Engineering Activities	\$0.20
Development of Processes and Equipment for Production of Phosphoric Acid. . . . .	.40
Agglomeration of Phosphate Fines for Furnace Use. . . . .	.30
Development of Processes for Production of Concentrated Superphosphate. . . . .	.45
Phosphorus: Properties of the Element and Some of Its Compounds.30
Corrosion Tests of Metals and Ceramics.20

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CORROSION TESTS OF METALS AND CERAMICS

Introduction

Although the literature on corrosion is voluminous, it is inadequate in that by its use the resistance of a particular material of construction to a corrosive medium under the conditions to be encountered in a proposed process seldom can be predicted with satisfying certainty. This is true because of the large number of variables that affect corrosion rates. To investigate the effects of all variables for a given material and corrosive is a tremendous task, and years of work remain before the field of the corrosion of materials will have been charted satisfactorily.

Because of these facts, the tests for which results are presented here were usually made to answer specific questions regarding the resistance of materials under conditions actually encountered. Therefore, the data obtained are discontinuous with respect to the effect of such variables as the concentration of the corrosive and temperature and the degree of aeration. They are presented as they were obtained, and in only a few cases has an effort been made to present correlations of the degree of attack with the variations in test conditions. A list of the TVA articles on corrosion is given in Index A.

Since the results presented are considered to be self-explanatory, no recommendations are made. It was not practical to test all the materials that might be suitable for a given application. Cost and immediate availability, as well as technical judgment, were the factors that limited the number of materials tested. Therefore, it is possible that some materials not included in the tests would have given results as good or better than those obtained with the materials tested, and it should not be inferred that the materials that proved to be satisfactory in the tests are the only ones that are suitable for use under the test conditions. It also is possible that certain materials were included in the tests at conditions under which their manufacturers would not recommend them for use. Failure of these materials to show satisfactory resistance to corrosion in these cases does not detract from their value for use under other conditions.

Many tests have been made on metals, ceramic materials, and protective coatings; however, it has been extremely difficult to evaluate

the results of the tests of the coatings, and this report is restricted to tests of the other two types of materials. The results of tests of metals and of ceramic materials are presented separately.

Tests of Metals

Metals were tested against compounds of phosphorus, nitrogen, sulfur, aluminum, and magnesium both in plant and pilot-plant equipment and in laboratory equipment set up especially for that purpose. The compositions of the metals used are shown in Index B. Only a few of the results of the tests made in plant or pilot-plant equipment are presented in the report because in such tests the precise control of conditions is difficult. In general, the testing procedures agree with those outlined by A. S. T. M. Designation A-224-46. In all cases, duplicate specimens were used, and some of the results presented are the average data obtained on as many as 10 specimens. The details of the three methods used in most of the laboratory tests and of the methods for handling specimens in the plant and pilot-plant tests are outlined below.

Methods of Testing

Thermal block laboratory tests.—Tests of disk-type specimens were run in thermal block corrosion-testing apparatus, one of which is shown in section in figure 1. A photograph of several of these apparatus is shown in figure 2. Specimens 1 to 2¼ inches in diameter and from ½ to ¾ inch thick, each having a hole $\frac{23}{64}$ inch in diameter at its center, were used in most of these tests. Where the determination of the effect of cold-bending the metal on its resistance to corrosion was desired, bent disk-type specimens were used. Welded specimens were prepared by cutting the disks in half, beveling the cut edges, and welding the halves together.

The specimens were hung on glass lift rods that are parts of the thermal block corrosion-testing apparatus. Each of the thermal blocks contained eight pyrex glass tubes 2½ inches in diameter and 20 inches long. These tubes extended into the blocks to a depth of 12 inches; for the tests the tubes were filled with the corrosive to the level of the top of the blocks (750 milliliter). The lift rods, which carried the specimens, were centered in the tubes and extended nearly to the tube bottoms. These rods were connected to cams that turned 19 revolutions per minute. The action of the cams lifted and lowered the rods through a distance of 1 inch. Thus, the average linear velocity of the specimens through the corrosive solution was 3.16 feet per minute. Cold water flowed through a coil in the top of each tube to prevent excessive loss of corrosive or of water through evaporation. When aeration of the specimen was desired, hollow lift rods were used, and air was passed through these rods at

the desired rate and emerged in the corrosive below the specimens. A flow of 0.02 cubic feet per minute of air was chosen arbitrarily as standard aeration in these tubes, and in the tables of data that follow, where the notation "with aeration" appears, that rate of flow was used. In some tests different rates of air flow were used. Each block was heated by means of five 1,000-watt Calrod units. The temperature of each block was controlled with a bimetal regulator inserted in a hole in the block at its center; this regulator controlled the flow of current to the Calrod units. The temperature in the tubes was controlled to within 3° F. of the desired value. This apparatus has been used in most of the laboratory tests.

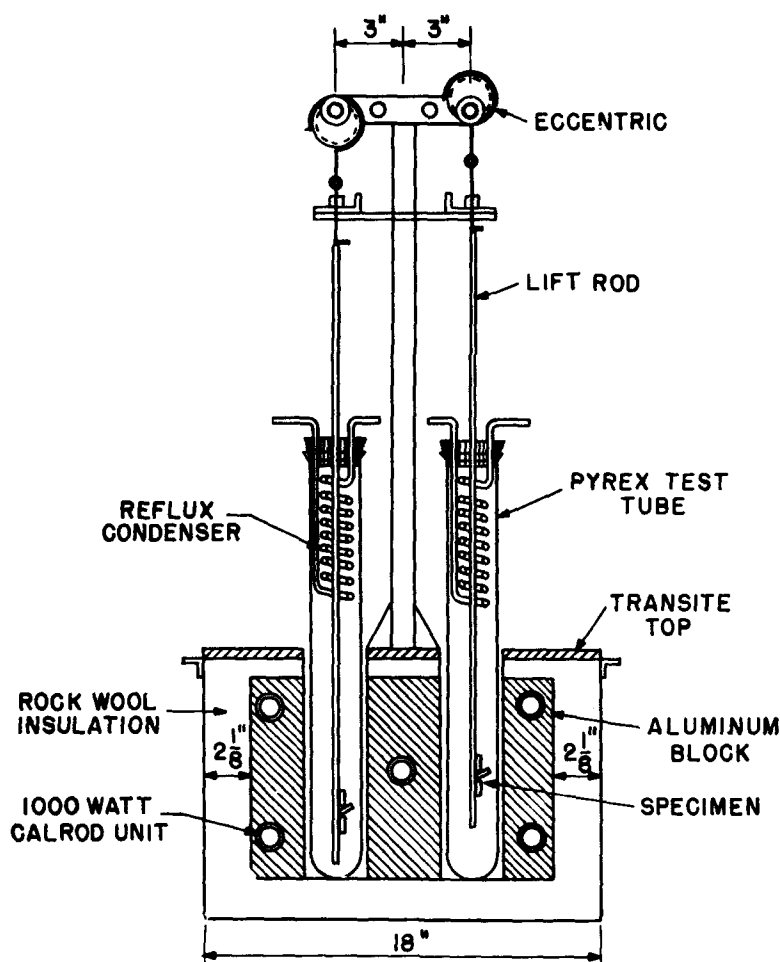


Figure 1.—Section through thermal block corrosion-testing apparatus.

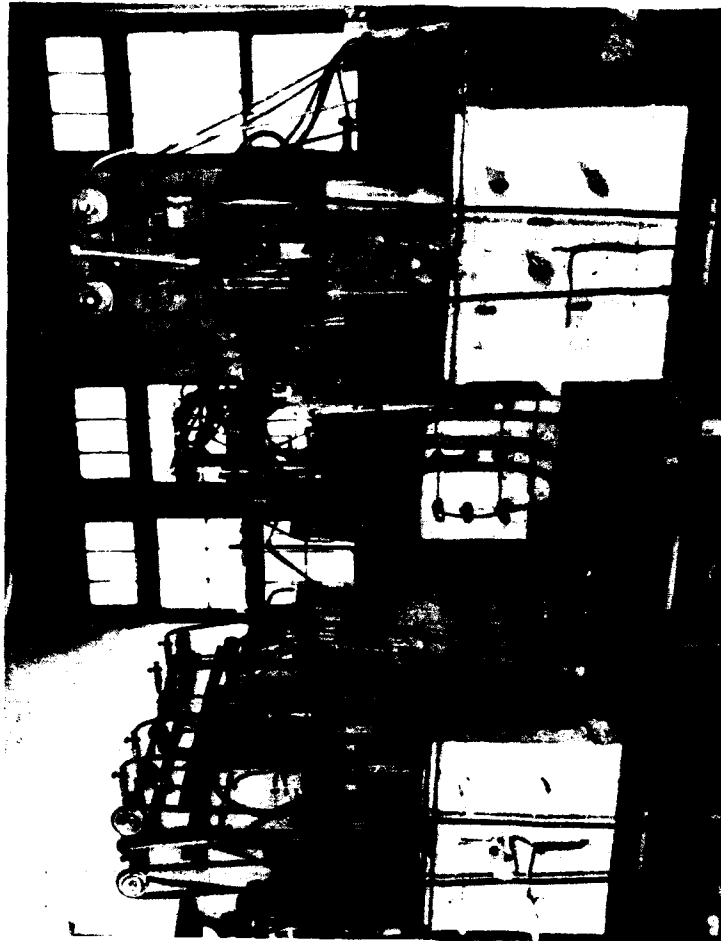


Figure 2.—Thermal block corrosion-testing apparatus.

The corrosives were placed in the tubes and brought to the desired test temperature before weighed test specimens were introduced. During the period of exposure of the specimens, the concentration of the corrosives was determined periodically to make certain that no significant change took place. At the end of the exposure period, the specimens were removed and scrubbed with a soft wire brush to remove corrosion products; then they were dried and weighed to determine weight loss.

Tests in ceramic-lined tank.—A number of tests of metals and ceramic materials were made in strong phosphoric acid containing 85 percent P_2O_5 (equivalent to 117 percent H_3PO_4) at 480° to 490° F. in a brick-lined steel tank. The tank, 37 by 37 by 22 inches deep, was lined on the sides with 8 inches of red shale brick and on the bottom with 4½ inches of that brick. Silica base, sodium fluosilicate-sodium silicate cement was used as a mortar in constructing the lining. The tank cover was made of Transite slabs 1 inch thick and was topped with heavy asbestos paper, which provided additional insulation. The acid in the tank was heated with four or five 1,000-watt Chromel-wound electric heaters encased in zircon-porcelain tubes, which were in a vertical position in the tank and extended upward through holes in the Transite cover. A Fenwal thermal regulator, immersed in transformer oil in a pyrex glass tube, was used for maintaining a constant acid-bath temperature. A photograph of the tank with a part of the cover removed is shown in figure 3. (Some of the heaters are not shown.)

Metal specimens were suspended in the acid by means of silver wires or were attached to lift rods on a cam-type mechanism so that they could be moved in the acid (average linear speed of 0.2 to 0.4 foot/minute) or alternately immersed and removed from the acid. Figure 3 shows a "spool" assembly of metal specimens suspended with silver wire but held above the acid level for photographing. Figure 4 shows how the spools were assembled. The cam mechanism for tests in which metal specimens were in motion is not shown in figure 3. The figure shows ceramic specimens in position for testing; ceramics usually were tested together with metals, and since they were rotated in the corrosive (usually at a speed of 14 revolutions per minute), their motion aided in agitating the corrosive.

In tests in which the acid in the bath was agitated only by the motion of the ceramic and metal specimens, the bath liquid velocity was not measured; in the table in which the results of these tests are presented, the notation "bath agitated slightly" appears. In tests in which the acid was agitated both by the motion of the specimens and by Lightnin mixers (only one of the two normally used is shown in fig. 3), the liquid velocity at the point where the metal specimens were immersed was measured with a Pitot tube. The maximum bath velocity at these points was 0.4 foot per second. The acid

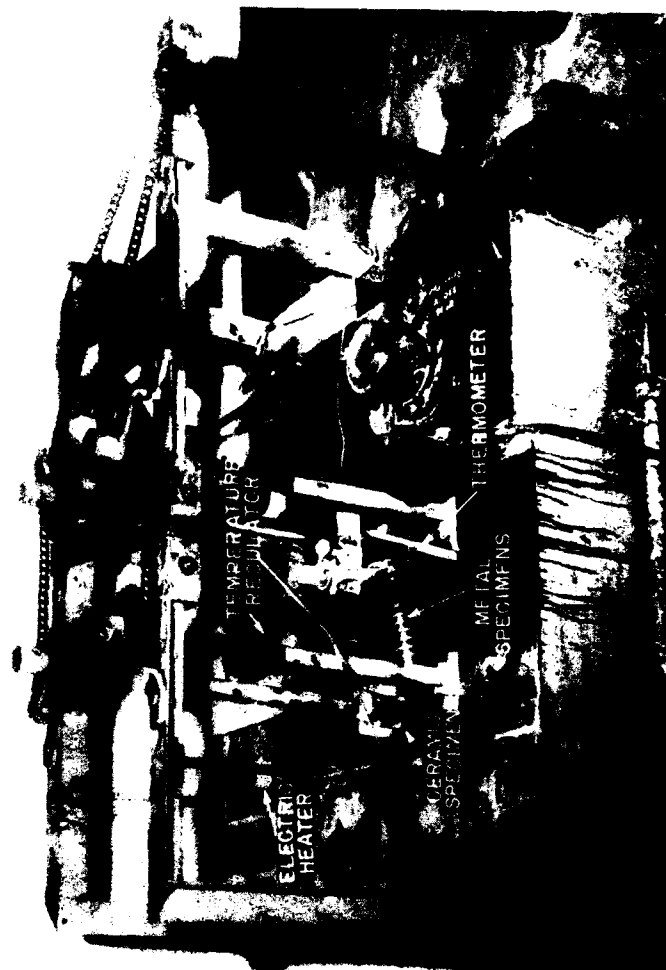


Figure 3.—Ceramic-lined tank for high-temperature corrosion tests.

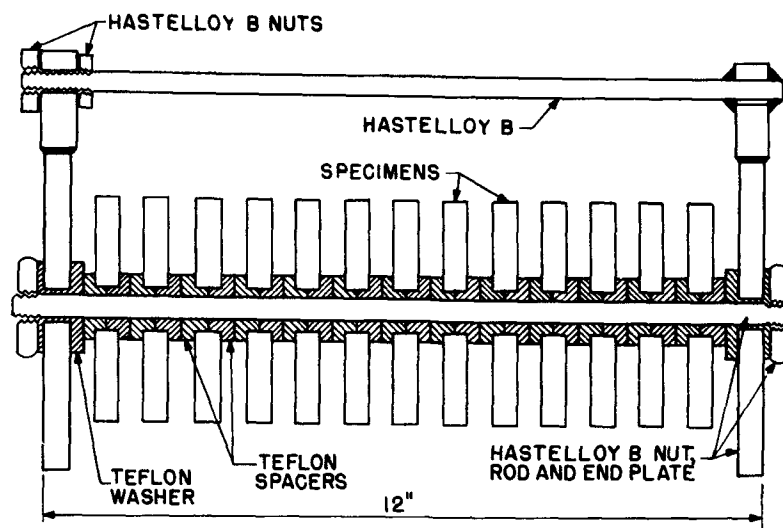


Figure 4.—Spool assembly of metal specimens for corrosion tests.

bath temperature was measured with a thermometer encased in a zircon-porcelain thermocouple-protection tube.

The metal specimens were weighed before and after the tests. The procedure used for cleaning the specimens was the same as that used in the thermal block tests.

Bomb tests.— For the tests in which it was necessary to use higher than atmospheric pressure, stainless steel bombs of the type shown in section in figure 5 were used. The metal specimens, which were of the disk type, were mounted as is shown in the figure. The bombs were provided with stainless steel adjustable pressure-relief valves to permit escape of gases formed during the test. When agitation of the corrosive was desired, the bombs were submerged in a constant-temperature water bath and oscillated with a cam mechanism. The cam turned 19 revolutions per minute and lifted and lowered one end of the bomb through a distance of 2 inches. At the middle of the stroke the axis of the bomb was horizontal. The water in the bath was heated with electric immersion heaters, and the temperature was controlled with a mercury thermoregulator.

In some tests these bombs were maintained stationary in a constant-temperature electric oven. The oven temperature was maintained at the desired value with a bimetallic thermal regulator that controlled the flow of current to its heating elements. The lines from the bombs to the relief valve were extended so that the valves were outside the oven.

The method of handling the specimens was the same as that described previously.

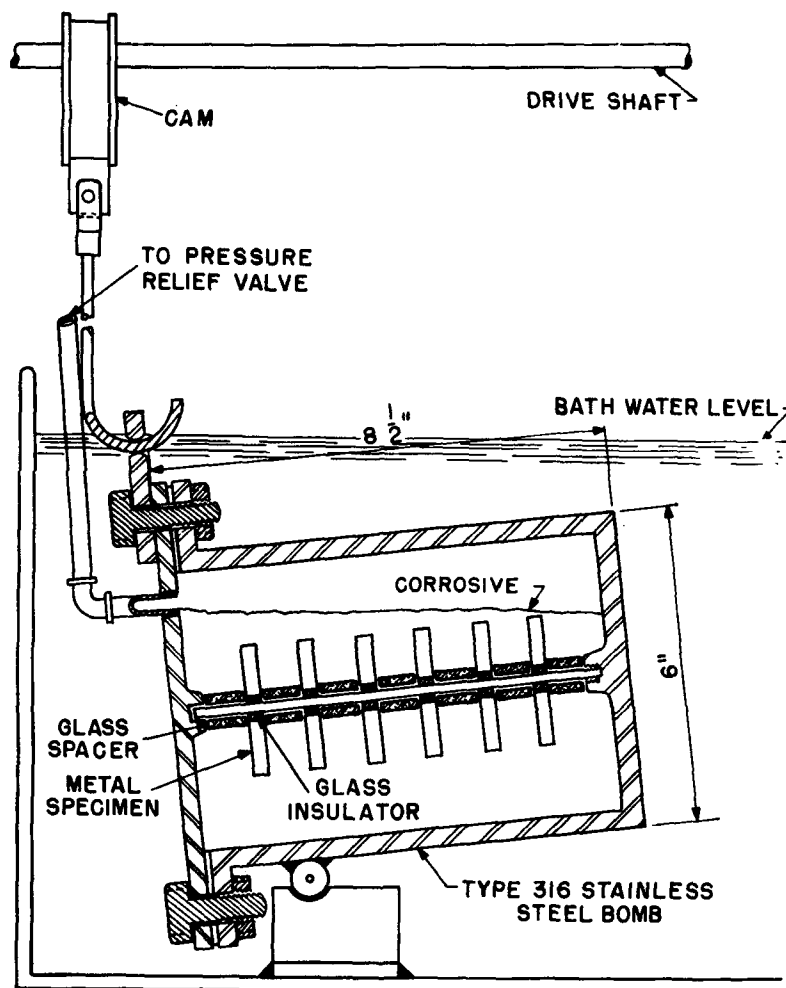


Figure 5.—Bomb corrosion-testing apparatus.

Plant and pilot-plant tests.—Tests were made in the plant and pilot plants in sumps, tanks, pipelines, launders, and reaction vessels of several types. Disk specimens were mounted on spools similar to the ones shown in figure 4. In most cases glass or Saran spacers were used in place of the Teflon ones shown in the figure, and the rods and end plates of the spools were usually made of A. I. S. I. Type 316 stainless steel.

The method of handling the specimens was the same as that described previously.

Method of Evaluation

In general, weight loss expressed as rate of corrosion in terms of mils of penetration per year was used as the basis for evaluating the resistance of a material to the corrosive. However, when the corrosion rate obtained in this manner was in the acceptable range but severe pitting of the test specimen had occurred, it was considered that corrosion was excessive, and this observation, instead of numerical data, is reported.

For use by TVA, 60 mils' penetration per year normally is considered the maximum acceptable rate. However, there are certain applications, for example, where thin materials must be used, in which the 60-mil criterion is not necessarily applicable.

The duration of most of the tests was 15 days or longer. It has been observed in a number of tests in phosphoric acid that corrosion rates are high at the beginning of the exposure period but decrease to a reasonably constant value after 6 days. Where data for tests of shorter than 6 days' duration are presented and the experimental rates are less than the normally accepted 60 mils per year, the rates are shown in tables to be presented later as less than the experimental value ($<$ experimental value). In those cases where the weight loss in less than a 6-day test period was so great that the corrosion rate calculated using this weight loss and a time of 6 days exceeded 60 mils per year, the corrosion rate has been shown only as "excessive." It was reasoned that, even if these tests had been extended to 6-day periods and no more metal had been corroded from the specimens, the rate still would have been excessive. Present TVA practice is to subject materials to a 30-day test. However, it is believed that, on the basis of recent data, the 6-day test results are significant and give an accurate indication of the serviceability of the materials tested.

Results of Tests

The results of tests in each type of corrosive are presented under a separate heading.

Tests in phosphoric acid.—Both electric-furnace phosphoric acid from the TVA acid plants and C. P. phosphoric acid were used in these tests. A typical analysis of plant acid (85 percent H_3PO_4) is as follows:

Constituent	Percent	Constituent	Percent	Constituent	Percent
P_2O_5	62.9	Pb.....	0.015	Si.....	0.01
K.....	.28	F.....	.024	C.....	.003
Ca.....	.20	Fe.....	.01	SO_3.....	.003
Na.....	.08	As.....	.003	Cu.....	.002
Al.....	.04	Mn.....	.002		

The results of laboratory tests made in the thermal block apparatus and in the bomb testing apparatus using plant acid are shown in table I, and the results of those made using C. P. acid are shown in

table II. The tests in C. P. acid were made in the thermal block apparatus. Table III shows the effect of varying the rate of aeration of both plant and C. P. 85 percent acid on the rate of corrosion of A. I. S. I. Type 316 stainless steel and of red brass as determined in the thermal block apparatus. In these tests several acid temperatures were used. The results of laboratory tests made in very strong phosphoric acid (117 percent H_3PO_4) at an elevated temperature (480° to 490° F.) are shown in table IV. The tests were conducted in the ceramic-lined tank testing apparatus, and the acid was prepared by concentrating plant acid (approximately 85 percent H_3PO_4) to 100 percent H_3PO_4 by evaporation and fortifying this acid with solid phosphorus pentoxide. The results of the tests in phosphoric acid that were made in plant and pilot-plant equipment are shown in table V. In these tests, acid concentration and temperature varied, and the extent of aeration and, in most cases, the velocity of agitation were not known.

TABLE I.—Laboratory corrosion tests in TVA plant phosphoric acid ^{1 2}

Material tested ¹	Corrosive and conditions	Corrosion rate expressed in mils penetration per year	
		With aeration	Without aeration
Admiralty metal.....	90 percent H_3PO_4 at 260° F.....	Exc.	.....
A. I. S. I. Type 304 stainless steel.....	1 percent H_3PO_4 +5 percent sugar at 363° F. and 160 p. s. i., bomb test.....	.....	0.9
Do.....	80 percent H_3PO_4 at 150° F.; metal cold bent 90° and heated to 850° F. and air-cooled.....	.....	.9
Do.....	80 percent H_3PO_4 at 240° F.....	Exc.	.....
Do.....	Boiling 80 percent H_3PO_4 at 294° F.....	.....	Exc.
Do.....	85 percent H_3PO_4 at 200° F.....	5.4	.....
Do.....	85 percent H_3PO_4 at 220° F.....	.....	Exc.
Do.....	85 percent H_3PO_4 at 255° F.....	Exc.	Exc.
Do.....	90 percent H_3PO_4 at 260° F.....	15	.....
Do.....	92 percent H_3PO_4 at 358° F.....	Exc.	.....
A. I. S. I. Type 309 stainless steel.....	80 percent H_3PO_4 at 240° F.....	<1.6	.....
Do.....	85 percent H_3PO_4 at 200° F.....	0	.....
Do.....	90 percent H_3PO_4 at 280° F.....	7	.....
A. I. S. I. Type 316 stainless steel.....	1 percent H_3PO_4 at 200° F.....	1	.1
Do.....	1 percent H_3PO_4 at 363° F. and 160 p. s. i., bomb test.....	.....	.9
Do.....	1 percent H_3PO_4 +5 percent sugar at 363° F. and 160 p. s. i., bomb test.....	.....	.3
Do.....	3 percent H_3PO_4 at 200° F.....	.1	.1
Do.....	5 percent H_3PO_4 at 200° F.....	.5	.1
Do.....	10 percent H_3PO_4 at 200° F.....	.1	.1
Do.....	20 percent H_3PO_4 at 200° F.....	.2	2
Do.....	40 percent H_3PO_4 at 200° F.....	.4	2
Do.....	60 percent H_3PO_4 at 200° F.....	5	1
Do.....	Boiling 70 percent H_3PO_4 at 260° F.....	.....	Exc.
Do.....	80 percent H_3PO_4 at 150° F.; metal cold bent 90° and heated to 850° F. and air-cooled.....	.....	.1
Do.....	80 percent H_3PO_4 at 180° F.....	2.5	.....
Do.....	80 percent H_3PO_4 at 180° F.; metal cold bent 90°, no subsequent heat treatment.....	2	.....
Do.....	80 percent H_3PO_4 at 180° F.; metal cold bent 90°, heated 15 minutes at 850° F. and air-cooled.....	2.4	.....
Do.....	80 percent H_3PO_4 at 200° F.....	3.2	.....
Do.....	80 percent H_3PO_4 at 200° F.; metal cold bent 90°, heated 15 minutes at 850° F. and air-cooled.....	2.2	.....
Do.....	80 percent H_3PO_4 at 200° F.; metal cold bent 90°, no subsequent heat treatment.....	4.7	.....
Do.....	80 percent H_3PO_4 at 240° F.....	<1.5	.....
Do.....	Boiling 80 percent H_3PO_4 at 294° F.....	.....	Exc.

See footnotes at end of table.

TABLE I.—Laboratory corrosion tests in TVA plant phosphoric acid ^{1 2}—Continued

Material tested ¹	Corrosive and conditions	Corrosion rate expressed in mils penetration per year	
		With aeration	Without aeration
A. I. S. I. Type 316 stainless steel	85 percent H ₃ PO ₄ at 200° F	1.2	
Do	85 percent H ₃ PO ₄ at 220° F	2	5
Do	85 percent H ₃ PO ₄ at 235° F	5	23
Do	85 percent H ₃ PO ₄ at 255° F	13	93
Do	85 percent H ₃ PO ₄ at 280° F	120	240
Do	85 percent H ₃ PO ₄ at 300° F	120	300
Do	90 percent H ₃ PO ₄ at 280° F	24	
Do	Boiling 90 percent H ₃ PO ₄ at 342° F		Exc.
Do	92 percent H ₃ PO ₄ at 358° F	Exc.	
Do	93 percent H ₃ PO ₄ at 260° F	260	
Do	93 percent H ₃ PO ₄ at 260° F; metal heated for 10 minutes in the range 1,600°-2,200° F. and water-quenched; specimen pickled in HF and HNO ₃ and passivated in concentrated HNO ₃	69	
Do	100 percent H ₃ PO ₄ ⁴ at 130° F	2	.3
Do	117 percent H ₃ PO ₄ ⁴ (85 percent P ₂ O ₅) at 140° F	<.1	
Do	117 percent H ₃ PO ₄ ⁴ (85 percent P ₂ O ₅) at 356° F		1.8
A. I. S. I. Type 316 stainless steel+Cb.	90 percent H ₃ PO ₄ at 260° F	17	
Do	93 percent H ₃ PO ₄ at 260° F	5	
A. I. S. I. Type 329 stainless steel	80 percent H ₃ PO ₄ at 150° F; metal cold bent 90°, heated to 850° F. and air-cooled.		28
Do	80 percent H ₃ PO ₄ at 200° F	2.4	
Do	80 percent H ₃ PO ₄ at 200° F; metal heated 16 hours at 760°-780° F. and air-cooled.	3.0	
Do	80 percent H ₃ PO ₄ at 240° F	<11	
Do	Boiling 80 percent H ₃ PO ₄ at 294° F		Exc.
Do	Boiling 90 percent H ₃ PO ₄ at 342° F		Exc.
Do	92 percent H ₃ PO ₄ at 358° F	Exc.	
Do	93 percent H ₃ PO ₄ at 260° F	320	
A. I. S. I. Type 347 stainless steel	85 percent H ₃ PO ₄ at 200° F	0	
Do	90 percent H ₃ PO ₄ at 260° F	8	
Do	93 percent H ₃ PO ₄ at 260° F	3	
A. I. S. I. Type 410 stainless steel	1 percent H ₃ PO ₄ at 200° F	.2	1
Do	3 percent H ₃ PO ₄ at 200° F	.2	44
Do	5 percent H ₃ PO ₄ at 200° F	5	57
Do	10 percent H ₃ PO ₄ at 200° F	6	38
Do	20 percent H ₃ PO ₄ at 200° F	180	38
Do	40 percent H ₃ PO ₄ at 200° F	400	490
Do	60 percent H ₃ PO ₄ at 200° F	1,800	510
A. I. S. I. Type 430 stainless steel	1 percent H ₃ PO ₄ at 200° F	.1	.1
Do	3 percent H ₃ PO ₄ at 200° F	1	.1
Do	5 percent H ₃ PO ₄ at 200° F	1.0	.1
Do	10 percent H ₃ PO ₄ at 200° F	1	2
Do	20 percent H ₃ PO ₄ at 200° F	1	.1
Do	40 percent H ₃ PO ₄ at 200° F	2	.1
Do	60 percent H ₃ PO ₄ at 200° F	10	15
Do	Boiling 70 percent H ₃ PO ₄ at 260° F		Exc.
Do	80 percent H ₃ PO ₄ at 200° F	3.1	16
Do	85 percent H ₃ PO ₄ at 220° F	13	
Do	85 percent H ₃ PO ₄ at 235° F		48
Do	85 percent H ₃ PO ₄ at 255° F		132
Do	80 percent H ₃ PO ₄ at 240° F	<5	
A. I. S. I. Type 446 stainless steel	85 percent H ₃ PO ₄ at 200° F	.6	
Do	90 percent H ₃ PO ₄ at 280° F	14	
A. I. S. I. Type 501 stainless steel	10 percent H ₃ PO ₄ at 200° F	2,300	
Do	20 percent H ₃ PO ₄ at 200° F	4,500	
A. I. S. I. Type 502 stainless steel	100 percent H ₃ PO ₄ ⁴ at 130° F	27	5
Aluminum	80 percent H ₃ PO ₄ at room temperature		1,130
Brass, high	70 percent H ₃ PO ₄ at 130° F		2.4
Do	78 percent H ₃ PO ₄ at 200° F		11
Do	85 percent H ₃ PO ₄ at 235° F		6
Do	85 percent H ₃ PO ₄ at 255° F		1
Do	90 percent H ₃ PO ₄ at 260° F	Exc.	
Brass, red.	1 percent H ₃ PO ₄ at 200° F	254	68
Do	1 percent H ₃ PO ₄ at 363° F. and 160 p. s. i. bomb test.		1.6
Do	1 percent H ₃ PO ₄ +5 percent sugar at 363° F. and 160 p. s. i. bomb test.		1
Do	3 percent H ₃ PO ₄ at 200° F	310	130
Do	5 percent H ₃ PO ₄ at 200° F	820	280

See footnotes at end of table.

TABLE I.—Laboratory corrosion tests in TVA plant phosphoric acid ^{1 2}—Continued

Material tested ¹	Corrosive and conditions	Corrosion rate—expressed in mils penetration per year	
		With aeration	Without aeration
Brass, red	10 percent H ₃ PO ₄ at 200° F.	640	142
Do	20 percent H ₃ PO ₄ at 200° F.	1,400	59
Do	40 percent H ₃ PO ₄ at 200° F.	1,630	50
Do	60 percent H ₃ PO ₄ at 200° F.	630	25
Do	85 percent H ₃ PO ₄ at 220° F.	630	21
Do	85 percent H ₃ PO ₄ at 235° F.	1,900	39
Do	85 percent H ₃ PO ₄ at 255° F.		98
Do	85 percent H ₃ PO ₄ at 280° F.	2,700	445
Do	85 percent H ₃ PO ₄ at 300° F.	5,500	81
Do	90 percent H ₃ PO ₄ at 260° F.	Exc.	
Do	Boiling 90 percent H ₃ PO ₄ at 342° F.		Exc.
Do	92 percent H ₃ PO ₄ at 358° F.	Exc.	
Do	100 percent H ₃ PO ₄ at 130° F.	8	2
Bronze, Phosphor C.	90 percent H ₃ PO ₄ at 260° F.	Exc.	
Bronze, Phosphor D.	90 percent H ₃ PO ₄ at 260° F.	Exc.	
Do	92 percent H ₃ PO ₄ at 358° F.	Exc.	
Chlorimet 2	80 percent H ₃ PO ₄ at 280° F.		9.5
Circle L-34 (cast)	80 percent H ₃ PO ₄ at 180° F.	44	
Do	80 percent H ₃ PO ₄ at 200° F.	32	
Do	90 percent H ₃ PO ₄ at 280° F.	300	
Do	92 percent H ₃ PO ₄ at 358° F.	Exc.	
Do	93 percent H ₃ PO ₄ at 260° F.	128	
Copper, deoxidized	1 percent H ₃ PO ₄ at 363° F. and 160 p. s. i., bomb test.		8
Do	1 percent H ₃ PO ₄ +5 percent sugar at 363° F. and 160 p. s. i., bomb test.		1
Do	65 percent H ₃ PO ₄ at 220° F.		46
Do	85 percent H ₃ PO ₄ at 235° F.		82
Do	85 percent H ₃ PO ₄ at 280° F.		130
Do	90 percent H ₃ PO ₄ at 260° F.	Exc.	
Durimet	117 percent H ₃ PO ₄ (85 percent P ₂ O ₅) at 140° F.	< 8	
Do	117 percent H ₃ PO ₄ (85 percent P ₂ O ₅) at 356° F.		1.6
Durimet 20	80 percent H ₃ PO ₄ at 255° F.	93	
Do	85 percent H ₃ PO ₄ at 255° F.		6.7
Do	85 percent H ₃ PO ₄ at 280° F.		47
Duriron (cast)	80 percent H ₃ PO ₄ at 280° F.		2.2
Do	85 percent H ₃ PO ₄ at 200° F.	1.7	
Do	85 percent H ₃ PO ₄ at 220° F.		1.8
Do	85 percent H ₃ PO ₄ at 235° F.		21.4
Do	90 percent H ₃ PO ₄ at 260° F.	4.2	
Do	90 percent H ₃ PO ₄ at 280° F.	9.9	
Everdur 1010	1 percent H ₃ PO ₄ at 363° F. and 160 p. s. i., bomb test.		1
Do	1 percent H ₃ PO ₄ +5 percent sugar at 363° F. and 160 p. s. i., bomb test.		.9
Do	70 percent H ₃ PO ₄ at 130° F.		5.7
Do	78 percent H ₃ PO ₄ at 200° F.		24
Do	85 percent H ₃ PO ₄ at 220° F.		21
Do	85 percent H ₃ PO ₄ at 255° F.		23
Do	85 percent H ₃ PO ₄ at 280° F.		180
Do	90 percent H ₃ PO ₄ at 260° F.	Exc.	
Do	92 percent H ₃ PO ₄ at 358° F.	Exc.	
Everdur 1015	90 percent H ₃ PO ₄ at 260° F.	Exc.	
Do	92 percent H ₃ PO ₄ at 358° F.	Exc.	
G-60 LaBour (cast)	117 percent H ₃ PO ₄ (85 percent P ₂ O ₅) at 140° F.	< 1.7	
Do	117 percent H ₃ PO ₄ (85 percent P ₂ O ₅) at 356° F.		2.7
Hastelloy A	80 percent H ₃ PO ₄ at 280° F.		54
Do	90 percent H ₃ PO ₄ at 260° F.	152	
Do	92 percent H ₃ PO ₄ at 358° F.	Exc.	
Do	93 percent H ₃ PO ₄ at 260° F.	260	
Hastelloy B	80 percent H ₃ PO ₄ at 255° F.	144	
Do	90 percent H ₃ PO ₄ at 280° F.	148	
Do	93 percent H ₃ PO ₄ at 260° F.	200	
Do	100 percent H ₃ PO ₄ at 130° F.	2	.7
Do	117 percent H ₃ PO ₄ (85 percent P ₂ O ₅) at 140° F.	0	
Illium G (cast)	117 percent H ₃ PO ₄ (85 percent P ₂ O ₅) at 140° F.	2.4	
Do	117 percent H ₃ PO ₄ (85 percent P ₂ O ₅) at 356° F.		2.2
Lead, chemical	56 percent H ₃ PO ₄ at 130° F.	16	7
Do	56 percent H ₃ PO ₄ at 160° F.	38	14
Do	56 percent H ₃ PO ₄ at 200° F.	57	25
Do	60 percent H ₃ PO ₄ at 200° F.	170	72
Do	Boiling 70 percent H ₃ PO ₄ at 280° F.		Exc.
Do	70 percent H ₃ PO ₄ +8 percent H ₂ SO ₄ at 130° F.		1.8
Do	70 percent H ₃ PO ₄ +8 percent H ₂ SO ₄ at 160° F.	166	88
Do	70 percent H ₃ PO ₄ +8 percent H ₂ SO ₄ at 200° F.	265	212
Do	78 percent H ₃ PO ₄ at 130° F.	36	8.4

See footnotes at end of table.

TABLE I.—Laboratory corrosion tests in TVA plant phosphoric acid^{1,2}—Continued

Material tested ³	Corrosive and conditions	Corrosion rate expressed in mils penetration per year	
		With aeration	Without aeration
Lead, chemical	78 percent H ₃ PO ₄ at 160° F	70	15
Do	78 percent H ₃ PO ₄ at 200° F	212	59
Do	80 percent H ₃ PO ₄ at 200° F	295	234
Do	Boiling 80 percent H ₃ PO ₄ at 294° F		Exc.
Do	85 percent H ₃ PO ₄ at 255° F	770	218
Do	85 percent H ₃ PO ₄ at 280° F		286
Do	Boiling 90 percent H ₃ PO ₄ at 342° F		Exc.
Lead, tellurium	70 percent H ₃ PO ₄ at 130° F		58
Do	78 percent H ₃ PO ₄ at 200° F		300
Low-chrome iron	80 percent H ₃ PO ₄ at room temperature		400
Manganese 18-8 stainless steel	85 percent H ₃ PO ₄ at 200° F	.1	
Mild steel	1 percent H ₃ PO ₄ at 363° F. and 160 p. s. i., bomb test		99
Do	100 percent H ₃ PO ₄ ⁴ at 130° F	59	1,000
Do	117 percent H ₃ PO ₄ ⁵ (85 percent P ₂ O ₅) at 100° F		<1
Do	117 percent H ₃ PO ₄ ⁵ (85 percent P ₂ O ₅) at 200° F		Exc.
Monel	1 percent H ₃ PO ₄ at 363° F. and 160 p. s. i., bomb test		8.4
Do	1 percent H ₃ PO ₄ +5 percent sugar at 363° F. and 160 p. s. i., bomb test		1.7
Do	85 percent H ₃ PO ₄ at 220° F		8.9
Do	85 percent H ₃ PO ₄ at 255° F	440	10
Do	85 percent H ₃ PO ₄ at 280° F		450
Do	117 percent H ₃ PO ₄ ⁵ (85 percent P ₂ O ₅) at 140° F	<10	
Do	117 percent H ₃ PO ₄ ⁵ (85 percent P ₂ O ₅) at 356° F		3.3
Monel K	117 percent H ₃ PO ₄ ⁵ (85 percent P ₂ O ₅) at 140° F	<9	
Do	117 percent H ₃ PO ₄ ⁵ (85 percent P ₂ O ₅) at 356° F		5.4
Muntz metal (cast)	90 percent H ₃ PO ₄ at 280° F	Exc.	
Do	92 percent H ₃ PO ₄ at 358° F	Exc.	
Pioneer	85 percent H ₃ PO ₄ at 255° F		100
R-55 La Bour (cast)	117 percent H ₃ PO ₄ ⁵ (85 percent P ₂ O ₅) at 140° F	<2.8	
Do	117 percent H ₃ PO ₄ ⁵ (85 percent P ₂ O ₅) at 356° F		4.3
Worthite	85 percent H ₃ PO ₄ at 220° F		24
Do	85 percent H ₃ PO ₄ at 255° F	50	70
Do	85 percent H ₃ PO ₄ at 280° F		110

¹ All tests were made in the thermal block testing apparatus (see fig. 1) unless otherwise noted. Other tests made in bomb testing apparatus. (See fig. 5.)

² Where "Exc." is shown in the table, corrosion is considered excessive.

³ Specimens were wrought metal unless the notation "cast" appears.

⁴ Plant acid concentrated by evaporation.

⁵ Plant acid concentrated to 100 percent H₃PO₄ by evaporation and fortified with P₂O₅.

TABLE II.—Laboratory tests in C. P. phosphoric acid ¹

Material tested ²	Corrosion rate expressed in mils penetration per year									
	1 percent H_3PO_4 at 200° F. with aeration	1 percent H_3PO_4 at 200° F. without aeration	3 percent H_3PO_4 at 200° F. with aeration	3 percent H_3PO_4 at 200° F. without aeration	5 percent H_3PO_4 at 200° F. with aeration	5 percent H_3PO_4 at 200° F. without aeration	10 percent H_3PO_4 at 200° F. with aeration	10 percent H_3PO_4 at 200° F. without aeration	20 percent H_3PO_4 at 200° F. with aeration	20 percent H_3PO_4 at 200° F. without aeration
A. I. S. I. Type 316 stainless steel	0.1	0.1	0.1	0.1	0.5	0.1	0.2	0.1	0.2	1
A. I. S. I. Type 410 stainless steel	.1	10	2	90	5	4	8	3	51	1
A. I. S. I. Type 416 stainless steel										2,600
A. I. S. I. Type 430 stainless steel	.1	.1	.1	.1	2	.1	2	.1	2	.1
A. I. S. I. Type 501 stainless steel							3,000		4,000	
Brass, red	180	115	320	112	880	120	660	56	160	15

Material tested ²	Corrosion rate expressed in mils penetration per year									
	40 percent H_3PO_4 at 200° F. with aeration	60 percent H_3PO_4 at 200° F. with aeration	60 percent H_3PO_4 at 240° F. with aeration	85 percent H_3PO_4 at 208° F. with aeration	85 percent H_3PO_4 at 208° F. without aeration	85 percent H_3PO_4 at 235° F. with aeration	85 percent H_3PO_4 at 235° F. without aeration	85 percent H_3PO_4 at 255° F. with aeration	85 percent H_3PO_4 at 280° F. with aeration	85 percent H_3PO_4 at 290° F. without aeration
A. I. S. I. Type 316 stainless steel	1	3	1	2	28	3	52	93	100	300
A. I. S. I. Type 410 stainless steel	3	24	41							24
A. I. S. I. Type 416 stainless steel										290
A. I. S. I. Type 430 stainless steel	.1	9	1							
A. I. S. I. Type 501 stainless steel										
Brass, red	18	1,120	11	470	10				2,700	108

¹ All tests were conducted in thermal block testing apparatus. (See fig. 1.)² All specimens were wrought metal.TABLE III.—Effects of aeration rate on corrosion of A. I. S. I. Type 316 stainless steel and red brass in 85 percent phosphoric acid at various temperatures ¹

Material ²	Aeration rate, c.f.m.	Corrosion rate in mils penetration per year									
		85 percent plant phosphoric acid temperature, ° F.					85 percent C. P. phosphoric acid temperature, ° F.				
		208	235	255	280	300	208	235	255	280	300
A. I. S. I. Type 316 stainless steel	0.000	5	23	10	240	300	28	52	93	300	290
Do.	.005	4	6	145	470	290	3	5	170	410	280
Do.	.010	3	8		280	320	1.4	3		280	260
Do.	.020	2	5		120	120	2	3		100	24
Do.	.030	2	7	30	140	63	1	3	18	25	30
Do.	.040	2	4	14	72		4	2	10	21	
Brass, red	.000	21	39		85	81	10			108	480
Do.	.005	240	540		660	1,800	330			1,390	2,400
Do.	.010	380	1,500		1,800	3,600	340			2,100	4,200
Do.	.020	610	1,900		2,700	5,500	470			2,700	5,800
Do.	.030	660	1,360		2,900	5,600	730			3,100	5,800
Do.	.040	770	1,550		3,300	6,800	750			3,200	6,600

¹ All tests were conducted in thermal block testing apparatus. (See fig. 1.)² All specimens were wrought metal.

TABLE IV.—Laboratory tests in 11% percent H_3PO_4 at 480° to 490° F.¹

Material tested ²	Corrosion rate expressed in mils penetration per year			
	Linear velocity of specimen 0.2 to 0.4 ft./sec.; specimen completely submerged; bath agitated slightly	Linear velocity of specimen 0.2 to 0.4 ft./sec.; specimen completely submerged; bath agitated 0.4 ft./sec.	Linear velocity of specimen 0.2 to 0.4 ft./sec.; specimen alternately submerged and removed from acid bath; bath agitated 0.4 ft./sec.	Specimen static; specimen completely submerged; bath slightly agitated
A. I. S. I. Type 309 stainless steel				2,700
A. I. S. I. Type 310 stainless steel				2,800
A. I. S. I. Type 316 stainless steel	1,090			
A. I. S. I. Type 317 stainless steel	540			
A. I. S. I. Type 347 stainless steel				3,300
A. I. S. I. Type 446 stainless steel				3,100
Brass, red	360			
Bronze, aluminum	530			
Bronze, Phosphor				2,300
Chlorimet 2 (cast)			39	
Circle L-34 (cast)	250			
Coast metal 4 (cast)				3,000
Coast metal 10 (cast)	200			
Coast metal 12 (cast)	200			
Coast metal 18 (cast)	170			
Durimet	800			
Duriron (cast)	300			
Elcomet K (cast)	700			
Everdur 1010	690			
Hastelloy A (cast and wrought)	32	30		
Hastelloy B (cast and wrought)		21	22	
Hastelloy C (cast)	120			
Hastelloy D (cast)	75			
Illium R	150			
Inconel	1,000			
La Bour G-60 (cast)	160			
La Bour R-55 (cast)	Exc.		Exc.	
Manganese 18-8 stainless steel	1,340			
Mild steel				1,000
Monel				Exc.
Nichrome V	125			
Nickel	Exc.			
Pioneer (cast)	200			
Sterling silver		12		
Tantalum				8
<i>Coupled samples</i>				
Hastelloy A (coupled with sterling silver)	310			
Hastelloy B (coupled with carbon)		28	27	
Hastelloy B (coupled with sterling silver)		4		
Sterling silver (coupled with Hastelloy A)	460			
Sterling silver (coupled with Hastelloy B)		Exc.		
<i>Welded samples</i>				
Hastelloy B (welded with Hastelloy B)		25	56	

¹ All tests conducted in ceramic-lined tank testing apparatus. (See fig. 3.)

² Specimens were wrought metal unless the notation "cast" appears.

TABLE V—Tests in plant phosphoric acid conducted in plant and pilot-plant equipment

Material tested ¹	Corrosion rate expressed in mils penetration per year												
	Solution containing 0.8 percent P_2O_5 and 0.4 percent H_2O_2 with pH 5.2, H_3PO_4 at velocity of 0.7 ft./min. at 139° F.	Solution containing less than 1 percent H_3PO_4 at 80° to 100° F.	Solution containing small quantity of phosphoric acid and 1 percent H_3PO_4 or less at 150° F.	3 to 14 percent H_3PO_4 containing small quantity of fluorine compounds at 150° F.	70 to 80 percent H_3PO_4 containing small quantity of fluorine compounds at 185° to 212° F.	70 to 80 percent H_3PO_4 (dripping) containing small quantities of fluorine compounds in a mist at 203° to 250° F.	75 to 80 percent H_3PO_4 at 167° F.	85 to 95 percent H_3PO_4 (dripping) containing small quantities of fluorine compounds in a mist at 212° to 259° F.	82 to 87 percent H_3PO_4 at 190° to 215° F.	85 to 95 percent H_3PO_4 containing small amount of fluorine compounds at 165° to 185° F.	117 percent H_3PO_4 (85 percent P_2O_5) at 445° to 465° F.	120 percent H_3PO_4 (87 percent P_2O_5) at 445° to 465° F.	Elemental phosphorus in storage at 140° to 158° F.
Admiralty Advance.			5.5	4.7	12.7	265	11.3	44		8.6			1.1
A. I. S. I. Type 302 stainless steel				2.7	22.5	620	24	64		11.1			1
A. I. S. I. Type 302 stainless steel welded with Type 302+Mo stainless steel welding rod.		1.0	3	.4	660	9.6	.6	45	580	2.8	980		
A. I. S. I. Type 303 stainless steel				.5	680	15.3	1	74		2.9			.4
A. I. S. I. Type 304 stainless steel			2	0	Exc.	350	800	1,430	Exc.	2,460			.2
A. I. S. I. Type 304 stainless steel welded with Type 304 stainless steel welding rod.			.5										
A. I. S. I. Type 316 stainless steel			0	0	112	7	3.5	36	21	3.2	180	Exc.	.1
A. I. S. I. Type 316 stainless steel welded with Type 316 stainless steel welding rod.			3.1										.6
A. I. S. I. Type 316 stainless steel welded to mild steel with Type 316+Cb welding rod.	0.8			.7	245	13	1.1	54		42	100		
A. I. S. I. Type 316 stainless steel welded to Type 316 with Type 316+Cb welding rod.													
A. I. S. I. Type 316 stainless steel welded to Type 316 with Type 316+Cb welding rod.	.1			0	3,955	34	14	660		610		350	Exc.
A. I. S. I. Type 320 stainless steel			.5										
A. I. S. I. Type 321 stainless steel													
A. I. S. I. Type 325 stainless steel			0										
A. I. S. I. Type 330 stainless steel		.7											
A. I. S. I. Type 430 stainless steel welded to mild steel with Type 316+Cb welding rod.	1.7												
A. I. S. I. Type 430 stainless steel welded to Type 430 with Type 316+Cb welding rod.	9												

A. I. S. I. Type 446 stainless steel.										
Allegany 55 (cast)										
AMSCO F-3 (cast)										
Anti-acid metal (cast)										
Beryllium copper										
Brass, high	1	6								
Brass, high (brazed with Phos-Copper)										
Brass, high (brazed with Sil-fos)										
Brass, high (brazed with Tobin bronze)										
Brass, high (brazed with 60 percent Sn)										
Brass, high (brazed with 60 percent Sn, 40 percent Pb solder)										
Brass, red (brazed to mild steel)	32									
Brass, red (brazed to red brass)	28									
Bronze, aluminum										
Bronze, manganese (cast)										
Bronze, nickel-aluminum (cast)										
Bronze, Phosphor C										
Bronze, Phosphor D										
Bronze, Superstrength (cast)										
Bronze, Tobin										
Carbide 20										
Cast iron, gray (cast)										
Cast iron, gray (malleable) (cast)										
Cast iron (brazed with Tobin bronze)										
Cast iron (cast)										
Cast iron (welded with cast iron) (cast)										
Circle L-34 (cast)										
Copper										
Copper (brazed with Phos-Copper)										
Copper (brazed with Sil-fos)										
Copper (brazed with Tobin bronze)										
Copper (soldered with 60 percent Sn, 40 percent Pb solder)										
Copper, deoxidized										
Crucible 9										
Crucible 20										
Cupronickel 20 percent										
Duralcan (cast)										
Duralcan (cast)										
Enduro NC-3 (cast)										
Everdur 1010										
Everdur 1015										
Hastelloy A										
Hastelloy A (welded with Hastelloy A rod)										
Hastelloy B										

See footnote at end of table.

TABLE V.—Tests in plant phosphoric acid conducted in plant and pilot-plant equipment—Continued

Material tested ¹	Corrosion rate expressed in mils penetration per year												
	Solution containing 0.8 percent P_2O_5 and 6.4 percent F_2 with pH 5.2, velocity of liquid 0.7 ft./min. at 130° F.	Solution containing less than 1 percent H_3PO_4 at 80° to 100° F.	Solution containing quantity of phosphorus and 1 percent H_3PO_4 at 150° F.	3 to 14 percent H_3PO_4 containing small quantity of fluorine compounds at 190° F.	70 to 80 percent H_3PO_4 containing small quantity of fluorine compounds at 185° to 212° F.	70 to 80 percent H_3PO_4 (dripping) containing small quantities of fluorine compounds at 230° to 240° F.	75 to 80 percent H_3PO_4 at 167° F.	85 to 95 percent H_3PO_4 (dripping) containing small quantities of fluorine compounds in a mist at 212° to 230° F.	82 to 87 percent H_3PO_4 at 190° to 215° F.	85 to 95 percent H_3PO_4 containing a small amount of fluorine compounds at 185° to 189° F.	117 percent H_3PO_4 (85 percent P_2O_5) at 430° to 455° F.	120 percent H_3PO_4 (87 percent P_2O_5) at 430° to 455° F.	Elemental phosphorus in solution at 146° to 156° F.
Hastelloy B (welded with Hastelloy B rod)													
Hastelloy C (cast)				0.2	2.6	6.8	0.6	21		0.4	60	35	0.2
Hastelloy D (cast)				.7	.7	3.2	1.1	5.1		.3	35	Exc.	.3
Illium G (cast)						6.2	1.1	42	200				
Inconel				1		187	12.8						1.7
Lead, chemical				.7		192	13.7						1.4
Lead, tellurium													
Low-chrome iron			22										
Low-chrome iron + Cb			31										
Medium-chrome iron			13										
Mild steel			80										
Mild steel (welded with mild steel rod)	6.8			31	Exc.		3,420		Exc.	8,310			4
Monel				2.8	60		24	75	22	14	580		.8
Monel K		5.7	1.5										
Monel S			5.5										
Muntz metal (cast)				1.4	11.3		4.4	8.2		6.2	170	Exc.	.5
Nichrome V													
Nickel				1.5	840	270	17.2	1,000		18			.3
Ni-Resist (cast)				3.3	240	162	67	360	120	175			1
Ni-Resist, copper free (cast)				15	430	470	25	430		18	1,400		.4
Olympic A				30	1,940	2,070	92	2,120	210	350			.3
Olympic D				3.6	8	110	6.1	43		4.7			1.9
Pioneer metal (cast)				4.6	8	255	7	50		5.8			2.3
Refractive metal (cast)				0	12.3	140	6.3	18		5.4	210	Exc.	0
Silicone 25-20 (cast)				2.9	8.2	440	11	100		7.6			0.3
Super nickel				0	1,990	410	45	1,650		290			0
Worthite (cast)		.1		0	26	330	11	100		7.6	360	Exc.	.7
Zorite				1.9	1,140	980	36	Exc.		71			1.7

¹ Specimens were wrought metal unless the notation "cast" appears.

Tests in vapor containing phosphoric acid.—Some tests were made in TVA phosphoric acid plant vapor ducts that contained phosphoric acid as mist and some fluorine, probably present as hydrogen fluoride. The principal constituent of the gas carrying the mist was nitrogen, though some oxygen and water vapor were present in all cases. The results of these tests are shown in table VI.

TABLE VI.—Tests in vapors containing phosphoric acid ¹

Material tested ²	Corrosion rate expressed in mils penetration per year			
	Vapor containing a small quantity of H_3PO_4 as a mist and traces of fluorine compounds at 185° to 212° F.	Vapor containing approximately 0.07 percent P_2O_5 by weight and approximately 264 p. p. m. F_2 and from 7 to 15 percent O_2 at a temperature from 129° to 237° F. Velocity of vapor approximately 30 ft./sec.	Vapor containing 10 percent by weight of 81 percent H_3PO_4 as a mist and approximately 250 p. p. m. F_2 by weight at 250° to 300° F.	Vapor containing approximately 13 percent P_2O_5 and approximately 250 p. p. m. F_2 by weight at 285° to 300° F. Velocity of vapor approximately 30 ft./sec.
Admiralty	45			40
Advance	37.5			
A. I. S. I. Type 302 stainless steel	2	37		
A. I. S. I. Type 302 stainless steel welded with Type 302+Mo stainless steel welding rod	2.5			
A. I. S. I. Type 303 stainless steel	2.3			
A. I. S. I. Type 304 stainless steel		190		
A. I. S. I. Type 309 stainless steel				1,200
A. I. S. I. Type 316 stainless steel	1.9	3.7	2.3	
A. I. S. I. Type 316 stainless steel welded with Type 316 stainless steel welding rod	3.2	1.7	2.9	
A. I. S. I. Type 316 stainless steel electric welded with Type 316+Cb stainless steel welding rod			6.3	
A. I. S. I. Type 316 stainless steel with Heliarc weld using Type 316+Cb rod for filler		4.3		
A. I. S. I. Type 317 stainless steel				350
A. I. S. I. Type 320 stainless steel	2.4			200
A. I. S. I. Type 329 stainless steel				
A. I. S. I. Type 430 stainless steel		12		
A. I. S. I. Type 430 stainless steel welded with Type 316+Cb welding rod		96		
A. I. S. I. Type 446 stainless steel				830
Allegheny 55 (cast)	2			
AMSCO F-3 (cast)	2.8			
Anti-acid metal (cast)	86			
Beryllium copper	54			46
Brass, high	73			
Brass, high (brazed with Phos-Copper)	61			
Brass, high (brazed with Sil-fos)	46			
Brass, high (brazed with Tobin bronze)	46			
Brass, high (soldered with 60 percent Sn, 40 percent Pb)	33			35
Brass, red	66	230		88
Brass, red (electric welded)				52
Brass, red (gas welded)		260		
Bronze, aluminum	300			
Bronze, commercial (cast)	46			18
Bronze, manganese (cast)	100			
Bronze, nickel-aluminum (cast)	100			
Bronze, Phosphor C	87			42
Bronze, Phosphor D	63			25
Bronze, silicon				46
Bronze, Superstrength (cast)	41			
Bronze, Tobin	21.4			202
Carpenter 20		5		
Cast iron, gray (cast)	62	Exc.		
Cast iron (brazed with Tobin bronze) (cast)	77			
Cast iron (welded with cast iron) (cast)	70			
Circle L-34 (cast)				37
Copper	64			

See footnotes at end of table.

TABLE VI.—Tests in vapors containing phosphoric acid ¹—Continued

Material tested ²	Corrosion rate expressed in mils penetration per year			
	Vapor containing a small quantity of H ₃ PO ₄ as a mist and traces of fluorine compounds at 185° to 212° F.	Vapor containing approximately 0.07 percent P ₂ O ₅ by weight and approximately 264 p. p. m. F ₂ and from 7 to 15 percent O ₂ at a temperature from 129° to 237° F. Velocity of vapor approximately 30 ft./sec.	Vapor containing 10 percent by weight of 81 percent H ₃ PO ₄ as a mist and approximately 250 p. p. m. F ₂ by weight at 250° to 300° F.	Vapor containing approximately 13 percent P ₂ O ₅ and approximately 250 p. p. m. F ₂ by weight at 285° to 300° F. Velocity of vapor approximately 30 ft./sec.
Copper (brazed with Phos-Copper)	60			
Copper (brazed with Sil-fus)	66			
Copper (brazed with Tobin bronze)	64			
Copper (soldered with 60 percent Sn, 40 percent Pb)	68			
Copper, deoxidized	41	240		87
Copper, deoxidized (electric weld)				75
Copper, deoxidized (gas weld)		260		79
Croloy 9	147			
Croloy 25 20	9			
Cupro-Nickel 20 percent	44			
Duralloy A	8			
Durichlor (cast)	37			
Duriron (cast)	35			5
Enduro NC 3 (cast)	11			
Everbrite (cast)	64			
Everdur 1010	32	120		
Everdur 1010 (electric weld with Everdur 1010 rod)		83		
Everdur 1015	32.5			
Gold				1
Hastelloy A	22.5			23
Hastelloy B		13		7
Hastelloy C (cast)	9			64
Hastelloy D (cast)	1.1			21
Illium G (cast)	13.2			
Inconel		350		
Lead, chemical	21.6	220		
Lead, tellurium	29.1			
Mild steel	36	Exc.		
Monel	44.5	150		310
Monel (electric welded with Monel)		170		
Monel (Helarc welded with Monel strip for filler)		160		
Monel K		160		90
Monel S (cast)	25	102		25
Monel S (electric weld with Monel No. 130-X rod)		71		
Muntz metal (cast)		114		77
Nichrome V	45			
Nickel	36.6	160		
Ni-Resist (cast)	85	460		
Ni-Resist, copper free (cast)	68	390		
Olympic A	42.5			
Olympic D	45			
Pioneer metal (cast)	6.5			50
Platinum				13
Resistac (cast)	38			
Silcorone 25-20	33			
Silver, fine			4.1	4
Sterling silver			5	5
Super nickel	31			
Worthing (cast)	1.5			
Zorite	71			

¹ All tests shown were conducted in plant equipment.² Specimens were wrought metal unless the notation "cast" appears.

Tests in solutions of phosphoric acid and other mineral acids and salts.—Tests were made in the laboratory in solutions containing phosphoric acid and other mineral acids and salts. C. P. chemicals were used. These tests were made in thermal block testing apparatus. The results are shown in table VII.

TABLE VII.—Tests in solutions of phosphoric acid¹ with other mineral acids and salts

Material tested:	Corrosion rate expressed in mils penetration per year							
	9 percent H_3PO_4 , 17 percent HCl , and 2 percent KCl solution with aeration at 140° F.	44 percent H_3PO_4 , 58.5 percent HNO_3 , and 1.5 percent NO_2 solution at 112° F. without aeration	46.2 percent H_3PO_4 , 61 percent HNO_3 , and 1.4 percent NO_2 at 125° F. without aeration	85 percent H_3PO_4 and 0.085 percent F_2 added as $K_2S_2F_8$ at 200° F. with aeration	85 percent H_3PO_4 and 0.085 percent F_2 added as $Na_2S_2F_8$ at 200° F. with aeration	85 percent H_3PO_4 and 0.085 percent F_2 added as NaF at 200° F. with aeration	85 percent H_3PO_4 and 0.085 percent F_2 added as KF at 200° F. with aeration	85 percent H_3PO_4 and 0.1 percent F_2 added as HF at 200° F. without aeration
A. I. S. I. Type 304 stainless steel		12						
A. I. S. I. Type 316 stainless steel		13		2	1	4	6	5
A. I. S. I. Type 329 stainless steel		76						
A. I. S. I. Type 430 stainless steel		84						
A. I. S. I. Type 416 stainless steel			25					
Brass, red				280	200	130	200	74
Durichlor (cast)	510							54
Durimet			13					
Hastelloy A	500		220					
Hastelloy B	340							
Monel			458					

¹ All tests conducted in thermal block testing apparatus. (See fig. 1.)

² Specimens were wrought metal unless the notation "cast" appears.

³ Solution made by adding solid P_2O_5 to fuming HNO_3 .

Tests in ammonium phosphate solutions.—Laboratory tests were made in solutions of monoammonium phosphate and diammonium phosphate. All tests were made in thermal block testing apparatus using salts made by the ammoniation of plant phosphoric acid in the pilot plant described by Thompson, et al. (8). The results are shown in table VIII.

Tests in electrostatic phosphorus precipitator seal oil with and without phosphorus and phosphorus pentoxide contamination.—A few tests were made in the laboratory in the oil used as a pressure seal for electrostatic dust precipitators used in phosphorus collection systems. New oil and also oil that had been in service were used. The oil was Navy No. 3095. The tests were made in a thermal block testing apparatus at 200° F. The oil was not aerated. Results are shown in table IX.

Tests in sulfuric acid with and without other materials.—Tests were made both in the laboratory and in pilot-plant equipment in sulfuric acid solutions both with and without other materials. In the pilot-plant tests the sulfuric acid that was used was produced in a pilot plant operated in a study of the production of alumina from clay (9). C. P. acid was used in the laboratory tests. The results are shown in table X. The methods of testing are indicated in the table. The extent of agitation and aeration in the pilot-plant tests is not known.

TABLE VIII.—Tests in ammonium phosphate solutions ¹

Material tested ²	Corrosion rate expressed in mils penetration per year								
	2 percent solution mono-ammonium phosphate at room temperature with aeration	2 percent solution mono-ammonium phosphate at room temperature without aeration	4 percent solution mono-ammonium phosphate at room temperature with aeration	4 percent solution mono-ammonium phosphate at room temperature without aeration	6 percent solution mono-ammonium phosphate at room temperature with aeration	6 percent solution mono-ammonium phosphate at room temperature without aeration	8 percent solution mono-ammonium phosphate at room temperature with aeration	8 percent solution mono-ammonium phosphate at room temperature without aeration	2 percent solution di-ammonium phosphate at room temperature with aeration
A. I. S. I. Type 430 stainless steel.....									
A. I. S. I. Type 501 stainless steel.....									
Brass, yellow.....	10	3	15	7.5	18	11	24	9	1
Cast iron, gray (cast).....									
Mild steel.....									

Material tested ²	Corrosion rate expressed in mils penetration per year—Continued								
	2 percent solution di-ammonium phosphate at room temperature without aeration	4 percent solution di-ammonium phosphate at room temperature with aeration	4 percent solution di-ammonium phosphate at room temperature without aeration	6 percent solution di-ammonium phosphate at room temperature with aeration	6 percent solution di-ammonium phosphate at room temperature without aeration	8 percent solution di-ammonium phosphate at room temperature with aeration	8 percent solution di-ammonium phosphate at room temperature without aeration	51 percent solution (saturated) diammonium phosphate at 140° F. with aeration	
A. I. S. I. Type 430 stainless steel.....									0
A. I. S. I. Type 501 stainless steel.....									33
Brass, yellow.....	2.5	1	2.6	3	7.2	5	9.4		25
Cast iron, gray (cast).....									26
Mild steel.....									

¹ All tests conducted in thermal block testing apparatus. (See fig. 1.)² Specimens were wrought metal unless notation "cast" appears.TABLE IX.—Tests in phosphorus electrostatic precipitator seal oil ¹ with and without P₂O₅ contamination ²

Material tested ³	Corrosion rate expressed in mils penetration per year	
	Precipitator seal oil without P ₂ O ₅ contamination at 200° F.	Precipitator seal oil containing phosphorus and weak H ₃ PO ₄ equivalent to 1.7 percent P ₂ O ₅ at 200° F.
A. I. S. I. Type 316 stainless steel.....	0.7	7
A. I. S. I. Type 316 stainless steel welded with Type 316 stainless steel rod.....		51
Mild steel.....	.4	200
Mild steel welded with mild steel.....		350
Red brass.....	.7	

¹ Precipitator seal oil S. A. E. 30 (Navy No. 3065).² Tests conducted in thermal block testing apparatus (see fig. 1) without aeration.³ All specimens were wrought metal.

TABLE X.—Tests in sulfuric acid solutions with and without other materials

Material tested ¹	Corrosion rate expressed in mils penetration per year												
	0.5 percent H ₂ SO ₄ at 365° F. and 160 p. s. l. without agitation; bomb test ²	0.5 percent H ₂ SO ₄ +5 percent sugar at 365° F. and 160 p. s. l. without agitation; bomb test ²	10 percent H ₂ SO ₄ +50 percent HNO ₃ at 150° F. without aeration; thermal block test ²	10 percent H ₂ SO ₄ +1 percent manganous acid at 175° F.; pilot-plant test ²	30 percent H ₂ SO ₄ at 70° F.; pilot-plant test ²	30 percent H ₂ SO ₄ at 175° F.; pilot-plant test ²	30 percent H ₂ SO ₄ boiling (228.4° F.) with aeration; thermal block test ²	40 percent H ₂ SO ₄ and 20 percent HNO ₃ at 150° F. without aeration; thermal block test ²	50 percent H ₂ SO ₄ at room temperature; test in pilot-plant storage tank ²	50 percent H ₂ SO ₄ at 90° F. without aeration; thermal block test ²	66 percent H ₂ SO ₄ at 90° F. without aeration; thermal block test ²	77.6 percent H ₂ SO ₄ at 90° F. without aeration; thermal block test ²	85 percent H ₂ SO ₄ at 90° F. without aeration; thermal block test ²
Advance													
A. I. S. I. Type 304 stainless steel													
A. I. S. I. Type 316 stainless steel													
A. I. S. I. Type 430 stainless steel	0.3	18	8.5	<1.6	550	190	Exc.	4.6	Exc.	217	Exc.	0.1	0.4
A. I. S. I. Type 501 stainless steel		3.3	3.5					13.2		Exc.	Exc.	13.4	86
A. I. S. I. Type 502 stainless steel			15.5					9.4		Exc.	Exc.	28.3	50
Brass, red	1.8	.4	12	Exc.	19				75				
Bronze, Phosphor C									42				
Bronze, Tobin					110			1.2		3.8			
Carpenter 20			1										1.1
Chlorimet 2 (cast)													
Chlorimet 3 (cast)													
Circle L-34						.5							
Copper, deoxidized	.7	.4		<1	3.2				28				
Duralumin					17								
Durichlor (cast)					9.4	6	69		390				
Duriron (cast)													
Elcomet K (cast)													
Everbrite (cast)													
Everdur 1010	2.2	.1		Exc.		210			36				
Hastelloy D (cast)					23	75							
Lead, chemical					2.5	1			7.1	.4	1.5	1.8	4.9
Lead, tellurium						9.4			6.9				
Mild steel													
Monel	190	.2			18					Exc.	Exc.	18.7	12.5
Monel K													
Monel S													
Monel metal (cast)				Exc.		130			130				
Pioneer metal (cast)						110							
Resistac (cast)													
Super nickel													
Worthite (cast)				Exc.		180			28	2.4			

¹ Specimens were wrought metal unless the notation "cast" appears.

² Testing apparatus shown in fig. 5.

³ Testing apparatus shown in fig. 1.

Tests in aluminum sulfate solutions.—Tests were conducted in the laboratory and in pilot-plant equipment (9) in aluminum sulfate solutions of several concentrations and at several temperatures. The aluminum sulfate was produced in the pilot plant. The results are shown in table XI. The methods of testing are indicated in the table. As was the case with tests in sulfuric acid, the extent of agitation and aeration obtained in the pilot-plant tests is not known.

TABLE XI.—Tests in aluminum sulfate solutions

Material tested ¹	Corrosion rates expressed in mils penetration per year										
	20 percent $\text{Al}_2(\text{SO}_4)_3$ at 140° F.; pilot-plant test	20 percent $\text{Al}_2(\text{SO}_4)_3$ and clay at 165° F.; pilot-plant test	20 percent $\text{Al}_2(\text{SO}_4)_3$ (boiling) at 218° F., with aeration; thermal block test ²	20 percent $\text{Al}_2(\text{SO}_4)_3$ (boiling) at 218° F., without aeration; thermal block test ²	20 to 30 percent $\text{Al}_2(\text{SO}_4)_3$ at 175° F.; pilot-plant test	24 percent $\text{Al}_2(\text{SO}_4)_3$ at 219° F.; pilot-plant test	30 percent $\text{Al}_2(\text{SO}_4)_3$ (boiling) at 220° F., with aeration; thermal block test ²	30 percent $\text{Al}_2(\text{SO}_4)_3$ (boiling) at 220° F., without aeration; thermal block test ²	30 to 40 percent $\text{Al}_2(\text{SO}_4)_3$ at 175° F.; pilot-plant test	40 to 50 percent $\text{Al}_2(\text{SO}_4)_3$ at 190° F.; pilot-plant test	50 to 55 percent $\text{Al}_2(\text{SO}_4)_3$ at 212° F.; pilot-plant test
A. I. S. I. Type 302 stainless steel		0							0	23	
A. I. S. I. Type 304 stainless steel			0.5	0.9			0.1		2	56	
A. I. S. I. Type 316 stainless steel		0	1.5	0	<0.3	0.1		0.5	0.2	3	
Ambrac A	21										
Brass, red		560				150					
Bronze, Phosphor D						190					
Bronze, Tobin		450				24					
Circle L-34 (cast)	.5		.9	.4	<.3		.2	.4	0	0	1.7
Copper, deoxidized		550			Exe.	140					
Durichlor (cast)	1.3								1.5	0	
Durimet			.5	16		4	.2	.3	0	.6	4.1
Duriron (cast)	5.1	2.9			<8.7				1.9	2.9	0
Everdur 1010											3
Lead, chemical	3.3	2.4			<2.5						2
Lead, tellurium	1										2.1
Monel		340									
Monel K						56					
Resistac (cast)	8.7								1.1	1.3	1.7
Super nickel	25										
Zorite	7.2										

¹ Specimens were wrought metal unless notation "cast" appears.

² Testing apparatus shown in fig. 1.

Tests in nitric acid.—Tests in nitric acid solutions of several concentrations and at several temperatures were made using both plant and C. P. acid in thermal block testing apparatus. The results of these tests are shown in table XII. Typical analysis of the plant acid used in these tests is given below.

Constituent	Percent	Constituent	Percent
HNO_3	42.5	Pb	Nil
Fe	.023	Cl	0.034
Al	.002	SiO_2	Nil
Ca	.004	SO_3	Nil
Mg	.004		

TABLE XII.—Tests in nitric acid ¹

Material tested ²	Corrosion rate expressed in mils penetration per year										
	7 percent (plant acid) HNO ₃ at 175° F. without aeration	30 percent (plant acid) HNO ₃ at 135° F. without aeration	40 percent (plant acid) HNO ₃ at 100° F. without aeration	40 percent (plant acid) HNO ₃ at 125° F. with aeration	41 percent (plant acid) HNO ₃ at 150° F. without aeration	42 percent (plant acid) HNO ₃ at 135° F. without aeration	42 percent (plant acid) HNO ₃ at 200° F. without aeration	43 percent (plant acid) HNO ₃ at 190° F. without aeration	50 percent (C. P. acid) HNO ₃ at 125° F. with aeration	60 percent (C. P. acid) HNO ₃ at 180° F. with aeration	70 percent (C. P. acid) HNO ₃ at 135° F. without aeration
A. I. S. I. Type 304 stainless steel	0.5	.....	.....	.....	.....	3.3	.....	.....	.....	2.6
A. I. S. I. Type 309 stainless steel	1.1	.....	.....	.....
A. I. S. I. Type 316 stainless steel	4.2	.....	.....	.....	.....
A. I. S. I. Type 347 stainless steel	4	.....	.....	.....
A. I. S. I. Type 430 stainless steel	1.1	41	.....	.....	1.3	.....	4	4	.....	5.2
A. I. S. I. Type 430 stainless steel electric welded with Type 309 stainless steel welding rod	3.7	.....	.....	.....	3	.....	.....
A. I. S. I. Type 430 stainless steel electric welded with Type 309+Cb stainless steel welding rod	1.4	.....	.....	.....	.....	.....	.....
A. I. S. I. Type 430 stainless steel electric welded with Type 316 stainless steel welding rod	2	.....	.....	.....	56	.....	.....
A. I. S. I. Type 430 stainless steel electric welded with Type 316+Cb stainless steel welding rod	2.5	.....	.....	.....	.....	.....	.....
A. I. S. I. Type 430 stainless steel electric welded with Type 347+Cb stainless steel welding rod	1.5	.....	.....	.....	.....	.....	.....
A. I. S. I. Type 430 stainless steel electric welded with Type 430 stainless steel welding rod	2.3	.....	.....	.....	12	.....	.....
A. I. S. I. Type 446 stainless steel	6	.....	.....	.....
A. I. S. I. Type 501 stainless steel
Aluminum (electric arc welded)	1.180	Exc.	.....	250	.....	.....	.....	.....	.....	.....	.....
Aluminum (gas welded)	500	.....	.....	.....	.....	.....	.....	.....
Aluminum (cast)	520	.....	.....	.....	.....	.....	.....	.....
A. S. T. M. Designation: A198-39, Grade A (cast)3	.....	.....	.....	.....	.....	.....	.....	.....	.....
A. S. T. M. Designation: A296-46T, Grade 8	0	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ferritic cast chromium steel (cast)	25	.....
Worthite3	.....	.....	.....	.....	.....	.....	.....	.....	.....

¹ All tests conducted in the thermal block testing apparatus. (See fig. 1.)² Specimens were wrought metal unless the notation "cast" appears.

Test in solutions containing ammonium nitrate with and without other materials.—Laboratory tests were made in solutions containing ammonium nitrate at several temperatures. Some of the solutions contained excess ammonia or calcium nitrate, and others contained compounds that had been added as corrosion inhibitors. The ammonium nitrate was made by the ammoniation of plant nitric acid. The calcium nitrate and the inhibitors were C. P. chemicals. The results of the tests are given in table XIII. The methods used in making the tests are indicated in the table.

TABLE XIII.—Tests in solutions containing ammonium nitrate with and without other materials

Material tested ¹	Corrosion rate expressed in mills penetration per year									
	30 percent NH_4NO_3 with pH 4.5 at 120° F.; special testing procedure. ²	30 percent NH_4NO_3 and 7 percent $\text{Ca}(\text{NO}_3)_2$ with pH 3.5 at 120° F.; special testing procedure. ²	60 percent NH_4NO_3 and 20 percent NH_4OH at 90° F. with agitation; bomb test. ³	70 percent NH_4NO_3 at 131° F. without aeration; thermal block test. ⁴	70 percent NH_4NO_3 containing 1,000 p. p. m. phosphoric acid as an inhibitor at 131° F. without aeration; thermal block test. ⁴	70 percent NH_4NO_3 containing 1,000 p. p. m. sodium chromate as inhibitor at 131° F. without aeration; thermal block test. ⁴	70 percent NH_4NO_3 at 150° F. without aeration; thermal block test. ⁴	75 percent NH_4NO_3 at 206° F. without aeration; specimen bent 35° before exposure; thermal block test. ⁴	75 percent NH_4NO_3 containing 0.1 percent $\text{Na}_2\text{Cr}_2\text{O}_7$ as inhibitor at 206° F. without aeration; specimen bent 35° before exposure; thermal block test. ⁴	75 percent NH_4NO_3 containing 0.1 percent $\text{K}_2\text{Fe}(\text{CN})_6$ as inhibitor at 206° F. without aeration; specimen bent 35° before exposure; thermal block test. ⁴
A. I. S. I. Type 304 stainless steel	0	0								
A. I. S. I. Type 405 stainless steel			0							
A. I. S. I. Type 410 stainless steel			0							
A. I. S. I. Type 416 stainless steel			0.5							
A. I. S. I. Type 430 stainless steel	0	0	0							
A. I. S. I. Type 430 stainless steel welded with Type 430 stainless steel welding rod			0							
A. I. S. I. Type 501 stainless steel			136							
A. I. S. I. Type 502 stainless steel			110							
Aluminum			0							
Aluminum welded with aluminum			0							
Cast iron, gray (cast)			150							
Durimet 20 (cast)							0			
Durimet T							0			
Lead, chemical	670	540								
Lead, tellurium	640	520								
Mild steel	130	230	120	16	25	19		3	1	1
Mild steel welded with mild steel			1,800			22				

¹ Specimens were wrought metal unless the notation "cast" appears.

² Test was conducted in an open water-jacketed beaker. The specimens moved at an average linear velocity of 20 feet per second being alternately immersed in the corrodent and removed from it 28 times per minute. Specimens were immersed approximately one-third of the time.

³ Testing apparatus shown in fig. 5.

⁴ Testing apparatus shown in fig. 1.

Test in copper ammonium acetate solution.—A test of several metals in copper ammonium acetate solution was made at 180° F. in plant equipment (4). The results are given in table XIV. The composition of the solution is shown in the table.

Tests in solutions of various compounds of fluorine.—Tests were made in the thermal block testing apparatus in solutions containing various compounds of fluorine. C. P. chemicals were used in preparing the solutions. The results are shown in table XV.

TABLE XIV.—Tests in copper ammonium acetate solution ^{1 2} at 180° F.

Material tested ²	Corrosion rate expressed in mils penetration per year
A. I. S. I. Type 316 stainless steel.....	0
A. I. S. I. Type 301 stainless steel.....	0.1
A. I. S. I. Type 302 stainless steel.....	0
Cast iron, gray (cast).....	2
Mild steel.....	.1

¹ Composition of solution:

Grams per liter

Acetic acid.....	120
NH ₃	154
Cupric ⁺	27
Cuprous ⁺	131

² Tests made in the plant, without aeration.³ Specimens were wrought metal unless the notation "cast" appears.TABLE XV.—Tests in solutions of various compounds of fluorine ¹

Material tested ²	Corrosion rate expressed in mils penetration per year								
	50 g./l. NaF at 200° F. with aeration	50 g./l. NaF at 200° F. without aeration	60 g./l. NH ₄ HF ₂ at 180° F. with aeration	60 g./l. NH ₄ HF ₂ at 180° F. without aeration	60 g./l. NH ₄ HF ₂ at 200° F. without aeration	NH ₄ F solution containing 53.4 g./l. F and 51.3 g./l. NH ₃ at 160° F. without aeration	10 percent HF+5 percent H ₂ SiF ₆ at 100° F. with aeration	10 percent HF+5 percent H ₂ SiF ₆ at 160° F. without aeration	10 percent H ₂ SiF ₆ at 160° F. without aeration
A. I. S. I. Type 302 stainless steel.....									160
A. I. S. I. Type 304 stainless steel.....					150				
A. I. S. I. Type 316 stainless steel.....		0		1	140	0			701
A. I. S. I. Type 410 stainless steel.....	0	0							8
A. I. S. I. Type 430 stainless steel.....									
Aluminum.....	0	0		125	610	0			
Brass, red.....	1	0	250	40	49	72	16		11
Brass, yellow.....	0	.7							
Bronze, leaded.....								31	
Bronze, Phosphor D.....								58	
Cast iron, gray (cast).....	.2	9							
Copper.....									13
Copper, deoxidized.....	.3	0						530	
Durimet.....							290		
Easy-Flo.....									9
Everdur 1010.....		.4					520		8.9
Hastelloy A.....							54		20
Inconel.....									9.3
Lead, chemical.....			3		66			45	210
Mild steel.....	.4	3		130		74			350
Monel.....	.2	0	65		72			16	12
Nickel.....									4
Silver, fine.....									1.5
Sterling silver.....							0.3		

¹ All tests were conducted in the thermal block testing apparatus. (See fig. 1.)² Specimens were wrought metal unless the notation "cast" appears.

Tests in magnesium chloride solutions containing small amounts of hydrochloric acid.—Tests were made in the thermal block testing apparatus in magnesium chloride solutions (14 percent) that contained small amounts of hydrochloric acid. These solutions were similar to some that were obtained in pilot-plant work (2) on the production of magnesium from olivine. The results are shown in table XVI.

TABLE XVI.—*Tests in magnesium chloride solutions containing small amounts of hydrochloric acid*¹

Material tested ²	Corrosion rate expressed in mils penetration per year			
	14 percent MgCl ₂ +small amount of HCl, pH 3, at room temperature without aeration	14 percent MgCl ₂ +small amount of HCl, pH 4, at room temperature without aeration	14 percent MgCl ₂ +small amount of HCl, pH 5, at room temperature without aeration	14 percent MgCl ₂ +small amount of HCl, at 120° F. without aeration
A. I. S. I. Type 303 stainless steel				4.7
A. I. S. I. Type 304 stainless steel				3.5
A. I. S. I. Type 329 stainless steel				1.3
A. I. S. I. Type 410 stainless steel				4
A. I. S. I. Type 430 stainless steel				3
A. I. S. I. Type 446 stainless steel				3
Brass, red				20
Brass, yellow				4
Cast iron, gray (cast)				30
Everdur 1010				6
Monel				1.5
Mild steel	4	3	2	
Super nickel				17

¹ All tests were conducted in the thermal block testing apparatus. (See fig. 1.)

² Specimens were wrought metal unless the notation "cast" appears.

Tests of Ceramic Materials

The results of tests made by four of the methods used for evaluating ceramic materials are given in this report. Each of these methods is outlined, and the basis for evaluating the results is explained in one of the following sections. The compositions and physical properties of the ceramic materials used in the tests are given in Index C.

Tests of Refractories Against Phosphates and Slags at Elevated Temperatures in a Pot-Type Furnace

Tests of the resistance of refractories to the corrosion action of phosphates and slags at elevated temperatures were made in a pot-type furnace. Corrosives tested were molten electric phosphate reduction furnace slag, calcium metaphosphate, rock phosphate, and basic open-hearth slag.

Equipment and procedure.—Four samples could be tested simultaneously in the furnace, which had a crucible that was 24 inches in diameter and 12 inches deep. As shown in figure 6, which is a cross-sectional drawing of the furnace, and in figure 7, which is a photograph

that shows the top of the furnace with the lid raised, the test specimens were suspended from the top by means of steel clamps; about 2 inches of the specimens was immersed in the molten corrosive. The furnace was heated by burning either fuel oil or carbon monoxide gas in two burner ports, tangential to the crucible and opening into the crucible above the pool of corrosive. Passage of the gaseous products of combustion over the molten corrosive caused it to be agitated somewhat, depending on the type of fuel used and the viscosity of the corrosive. However, agitation was not considered to be very significant and was not measured in all the tests. The degree of agitation is indicated by measurement made when using molten slag from electric phosphate reduction furnaces as the corrosive. With oil as fuel and a temperature of about 2,500° F., the molten slag in the crucible appeared to rotate at a speed of 6 revolutions per minute. With carbon monoxide as fuel, under the same conditions, the rotational speed was about 4 revolutions per minute.

The furnace temperature was controlled and recorded by means of a potentiometer-type pyrometer. A calibrated platinum-platinum-10 percent rhodium thermocouple in a porcelain protection tube was used to measure furnace temperature. This thermocouple was guarded from fumes and slag attack by a standard Carbofrax protection tube.

The corrosive was charged into the furnace and melted in such a manner that contact of the cold unmelted material with the test brick was avoided. The lid and the space around each brick in the lid were sealed, and gases left the furnace through flues in the side of the furnace. The heating schedule, the maximum temperature reached, and the time at the maximum temperature varied for the different corrosives tested. The bath level was maintained constant by additions of the corrosive during the testing period.

At the end of the test period the corrosive was tapped from the furnace while the temperature was maintained at the maximum that had been attained so that the molten corrosive would drain from the specimens. The tapping period usually required 10 to 15 minutes, and when tapping was complete, the furnace was shut off and allowed to cool for 12 to 24 hours.

The specimens then were detached from the clamps, and the approximate average depth of penetration of corrosion and erosion was determined. The measurements were taken at the surface of the molten corrosive since in practically all cases the greatest amount of penetration occurred at this point. The depth determinations were made by laying a straightedge along the face of the uncorroded part of the test specimen so that it extended over the corroded section and then measuring the distance from the straightedge to the surface that had been attacked by the corrosive.

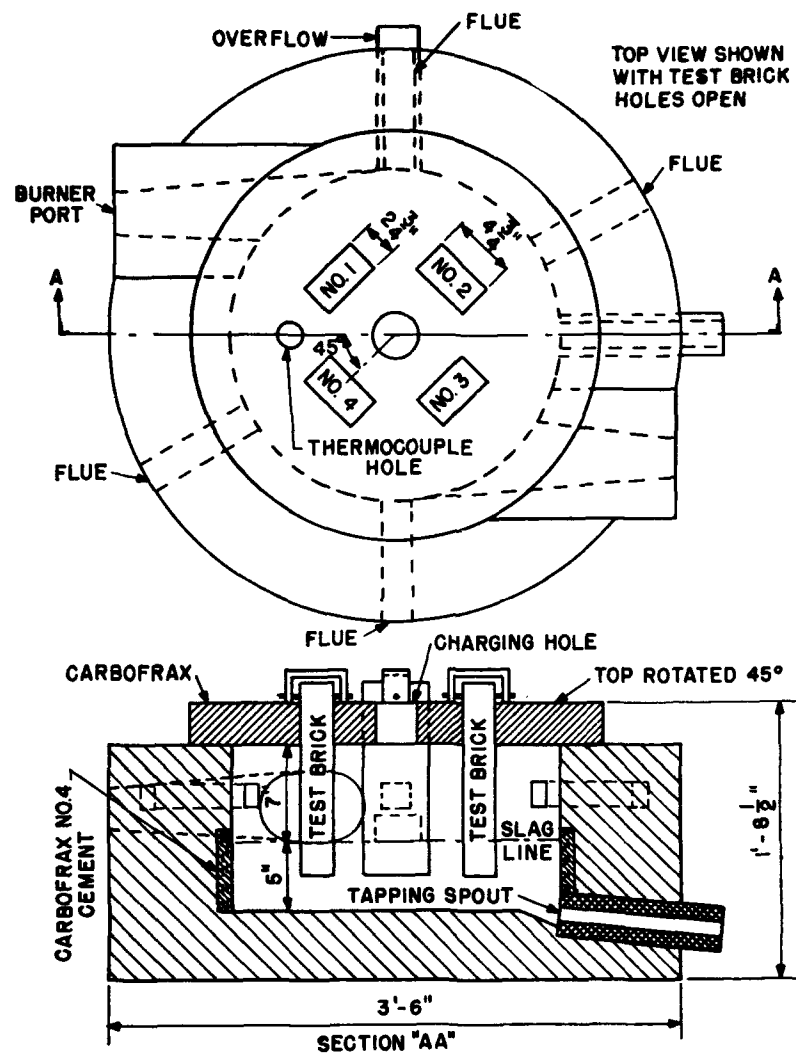


Figure 6.—Pot-type refractory testing furnace.



Figure 7.—Pot-type test furnace with lid raised.

Results.—Evaluations of the tests of ceramic materials were made on the basis of the approximate average depth of penetration of corrosion and erosion for two or more specimens. In the tables that follow, the brick are arranged in the order of increasing depths of penetration. In several cases, evaluation on this basis could not be followed because the test brick absorbed slag, expanded, or cracked to such an extent that they were considered unsatisfactory for use in refractory structures. The method of evaluation used here is somewhat different from that described in other articles (5, 6) concerning this work, but the conclusions reached are essentially identical, and it is believed that the present method is the more reliable.

The results of tests of the corrosiveness of electric-furnace slag, calcium metaphosphate, fused rock phosphate, and basic open-hearth slag are presented, respectively, in tables XVII, XVIII, XIX, and XX. Photographs of some of the exposed test brick are shown in figure 8 through 11.

TABLE XVII.—Results of tests in molten slag¹ from electric phosphate reduction furnace

[Maximum temperature, 2,650° F.]²

Material tested—brick	Maximum penetration (inches) ³	Remarks
Calcium oxide—chromium oxide—zirconium oxide. ^{4 5}	0 to 3/16	Sides smooth, absorbed slag.
Calcium oxide—chromium oxide. ^{5 6}	0 to 3/16	Sides smooth, attacked at flux line only, absorbed slag.
Fused cast (approximately 70 percent Al ₂ O ₃).	3/16	Sides smooth, attacked at flux line only, no slag absorbed.
Fused cast (approximately 90 percent Al ₂ O ₃).	3/8 to 3/16	Sides smooth, no slag absorbed, some pipes in the test bricks were exposed by the attack of the slag.
Zircon.	1/4 to 1/4	Sides smooth.
Electrocast (approximately 75 percent Al ₂ O ₃).	1/4 to 1/2	Sides smooth, some pipes in test bricks were exposed by the attack of the slag.
Aluminous (approximately 70 percent Al ₂ O ₃).	1/4 to 9/16	Sides rough.
Aluminous (approximately 90 percent Al ₂ O ₃).	3/8 to 1/2	Sides very rough.
Aluminous (approximately 50 percent Al ₂ O ₃).	3/8 to 1/2	Sides smooth, few coarse grains protruding.
Zircon—silicon carbide.	2/16 to 15/16	Sides smooth, bottom end rough.
Super duty fireclay.	3/8 to 3/4	Sides smooth.
Forsterite-Chrome.	1/4 to 3/8	Sides smooth, honeycombed, absorbed slag.
Fused cast (approximately 50 percent MgO).	2/16 to 13/8	Sides rough, badly honeycombed, absorbed slag.
Silica.	3/16 to 13/4	Sides smooth, all specimens honeycombed on bottom.
Calcium oxide—zirconium oxide. ^{1 7}	1/16 to 1/4	Sides rough, absorbed slag.
Chrome.	4/16 to 3/8	Sides rough, slight bloating, checked.
Chrome-Magnesia.	1/4 to 3/8	Sides rough, honeycombed, absorbed slag.
Aluminous (approximately 60 percent Al ₂ O ₃).	3/8 to 3/4	Sides smooth, one specimen absorbed slag excessively, the other shrank slightly and both had a few rough spots.
Forsterite.	1/2 to 1.	Sides smooth, honeycombed, absorbed slag excessively.
Magnesite.	Cut off.	Sides smooth, bloated above flux line, softened.

¹ Chemical analysis: SiO₂, 39.5 percent; CaO, 48.2 percent; P₂O₅, 0.9 percent; Al₂O₃, 10 percent; Fe₂O₃, 0.3 percent; MgO, 0.2 percent; and F, 2.6 percent.

² Furnace with some slag heated to 750° to 900° F. in 9 hours, and the temperature was raised to 2,000° to 2,200° F. in 8 hours. Remainder of slag was charged and the furnace heated to 2,650° F. in 2 hours. Furnace held at this temperature for 2 hours.

³ The brick are arranged in the order of depth of penetration except when the test bricks absorbed slag, expanded, or cracked to such an extent that they would be unsatisfactory for use in refractory structures.

⁴ U. S. Patent 2,231,944, Feb. 18, 1941.

⁵ Test bricks were fabricated in the laboratory by the dry press process. They were pressed at 370 to 470 pounds per square inch and fired to 1,500° C.

⁶ U. S. Patent 2,231,024, Feb. 11, 1941.

⁷ U. S. Patent 2,231,945, Feb. 18, 1941.

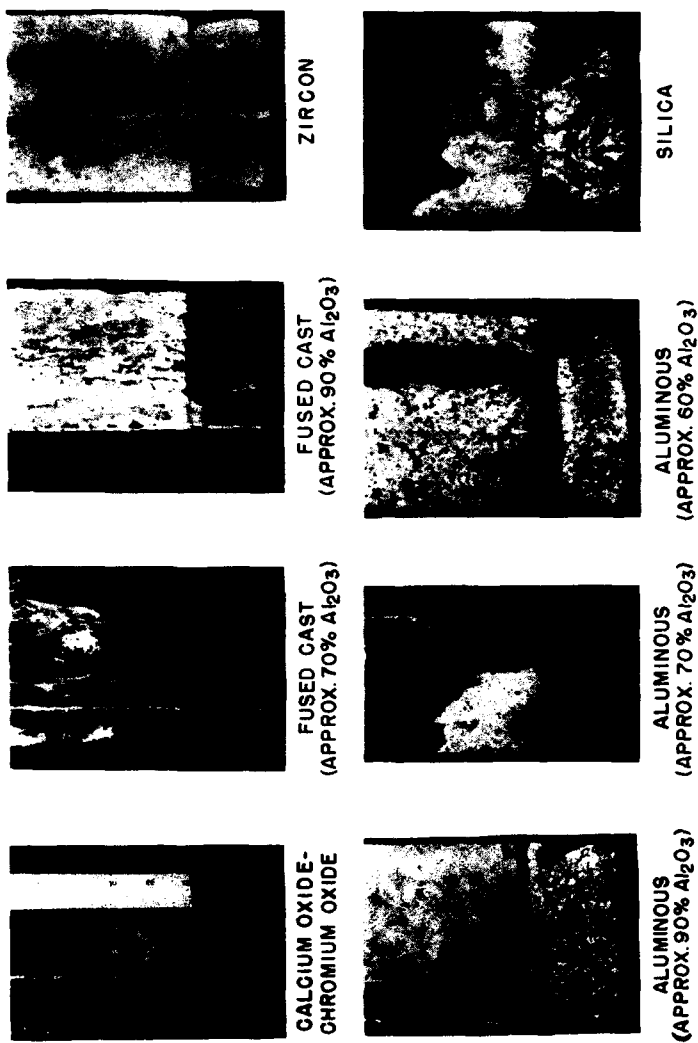


Figure 8.—Submerged ends of refractories after exposure to molten electric-furnace slag at 1,450° C. (2,642° F.).

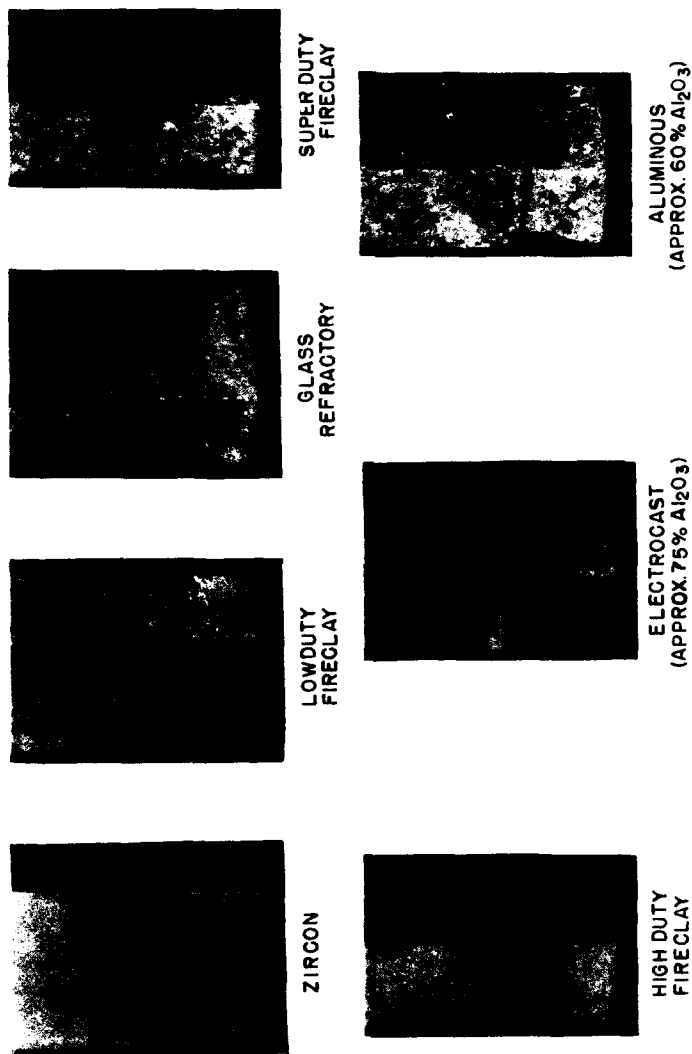


Figure 9.—Submerged ends of refractories after exposure to molten calcium metaphosphate at 1,300° C. (2,372° F.).

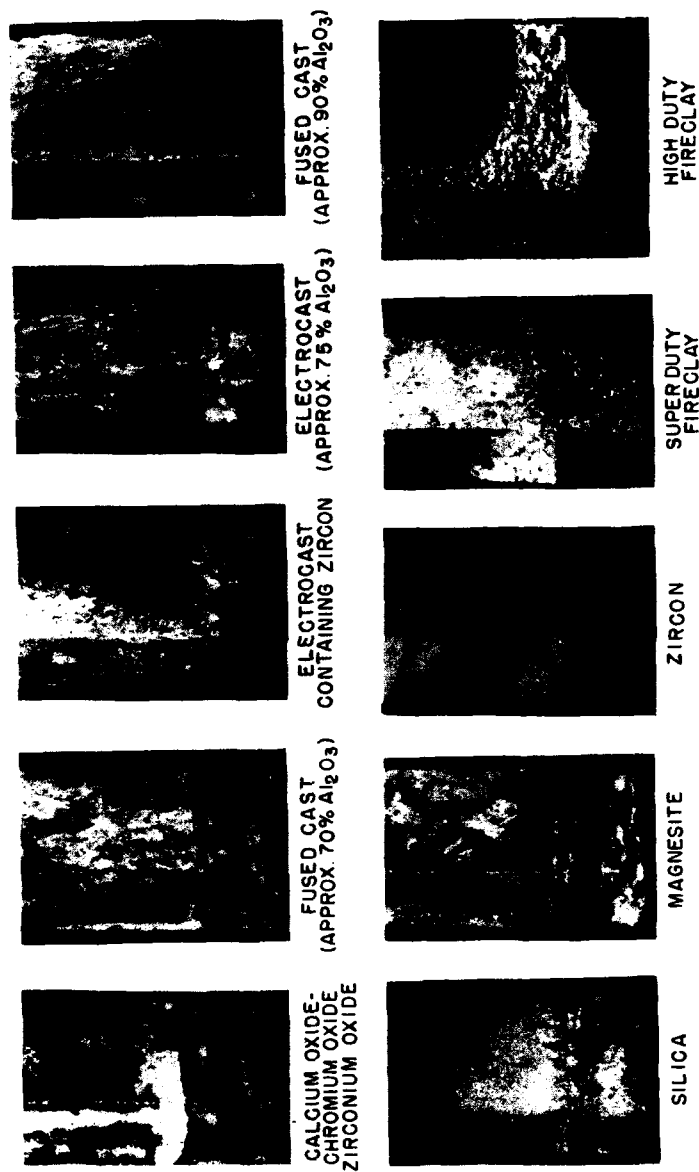
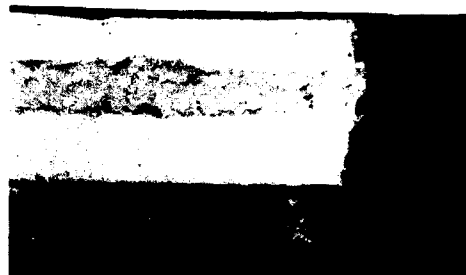


Figure 10.—Submerged ends of refractories after exposure to molten rock phosphate at 1,550° C. (2,822° F.).



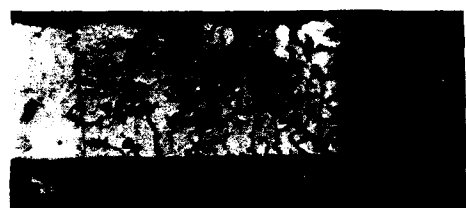
FORSTERITE - CHROME



CHROME



MAGNESIA - CHROME



FUSED CAST
(APPROX. 90% Al_2O_3)



FUSED CAST
(APPROX. 70% Al_2O_3)

Figure 11.—Submerged ends of refractories after exposure to molten basic open-hearth slag at 1,550° C. (2,822° F.)

TABLE XVIII.—Results of tests in molten calcium metaphosphate ¹[Maximum temperature, 2,375° F.] ²

Material tested—brick	Maximum penetration (inches) ³	Remarks
on	$\frac{1}{16}$ to $\frac{1}{8}$	Sides smooth, medium to very fine honeycombing on bottom, expanded very slightly.
Used cast (approximately 90 percent Al_2O_3).	$\frac{1}{8}$ to $\frac{1}{4}$	Sides smooth, medium honeycombing on bottom.
Low duty fireclay	$\frac{1}{8}$ to $\frac{1}{4}$	Sides smooth, fine honeycombing on bottom, expanded slightly.
Glass refractory	$\frac{1}{4}$ to $\frac{5}{32}$	Sides moderately smooth, fine honeycombing on bottom.
Super duty fireclay	$\frac{1}{8}$ to $\frac{5}{32}$	Sides rough, coarse-to-coarse interconnecting honeycombing on bottom with coarse protruding particles on sides and bottom.
High duty fireclay	$\frac{1}{8}$ to $\frac{5}{16}$	Sides smooth to rough, fine-to-coarse interconnecting honeycombing on bottom.
Fused cast (approximately 70 percent Al_2O_3).	$\frac{3}{16}$ to $\frac{1}{4}$	Sides smooth, coarse honeycombing on bottom.
Electrocast containing zircon	$\frac{1}{4}$	Sides smooth, coarse honeycombing on bottom.
Electrocast (approximately 75 percent Al_2O_3).	$\frac{1}{4}$ to $\frac{5}{16}$	Sides smooth, coarse honeycombing on bottom.
Aluminous (approximately 60 percent Al_2O_3).	$\frac{1}{4}$ to $\frac{5}{16}$	Sides moderately smooth to rough, coarse honeycombing on bottom, one specimen had coarse protruding particles on sides and bottom.
Zircon—silicon carbide	$\frac{3}{16}$ to $\frac{1}{2}$	Sides rough, fine honeycombing on bottom, coarse protruding particles on sides and bottom.
Fused cast (approximately 50 percent MgO).		End corroded off after 18 hours of test.

¹ Chemical analysis: SiO_2 , 3.3 to 4.6 percent; CaO , 24 to 26.9 percent; P_2O_5 , 66.2 to 67.5 percent; Al_2O_3 , 1.5 to 2 percent; Fe_2O_3 , 1.7 to 1.8 percent; and F , 0.3% to 0.50 percent.² Furnace with some calcium metaphosphate heated to 1,000° F. in 4 hours. Remainder of calcium metaphosphate was charged and furnace heated to 2,375° F. in 2 hours. Furnace held at this temperature for 66 hours.³ Brick are arranged in the order of depth of penetration.*Tests of Refractories Against Pellets of Phosphates and of Lime*

Equipment and procedure.—Tests to determine the resistance of various refractory materials to phosphates and lime at elevated temperatures were made by the procedure of Hugill, Ainsworth, and Green (3) for determination of the corrosive action of lime on aluminous fireclay and silica brick. The corrosives were prepared by fine grinding and then forming into cylindrical pellets, approximately $1\frac{1}{8}$ inches in diameter, at 3,000 pounds per square inch pressure. A pellet was placed on the surface of the brick being tested, and the brick and pellet were heated to test temperature (2,650° or 2,825° F.) in an electric furnace in 21 to 22 hours, held at this temperature

TABLE XIX.—Results of tests in molten rock phosphate ¹[Maximum temperature 2,825° F.] ²

Material tested—brick	Maximum penetration (inches) ³	Remarks
Calcium oxide—chromium oxide—zirconium oxide ^{4,5}	½ to ¾	Sides smooth, absorbed melt, slight expansion.
Fused cast (approximately 70 percent Al ₂ O ₃).	½ to ¾	Sides smooth, some pipes in the test bricks were exposed by the attack of the phosphate.
Electrocast containing zircon.	¼ to ½	Do.
Electrocast (approximately 75 percent Al ₂ O ₃).	¾ to 1	Do.
Fused cast (approximately 90 percent Al ₂ O ₃).	¾	Do.
Silica	¾ to ¾	Sides smooth, absorbed melt.
Calcium oxide—chromium oxide ⁶	¾	Sides smooth, absorbed melt, slight expansion.
Chrome-Magnesia.	½ to ¾	Sides smooth, cracked on cooling, absorbed melt and expanded.
Calcium oxide—zirconium oxide ⁷	¼ to ¾	Sides smooth, absorbed melt, cracked on cooling and expanded.
Magnesite.	¾ to 1	Sides smooth, both specimens deformed, absorbed melt, cracked, end dropped off of 1 after 4 hours at maximum temperature.
Zircon.	¼ to 1	Sides smooth, 1 specimen expanded and absorbed melt, the other expanded slightly and the end was corroded off.
Aluminous (approximately 50 percent Al ₂ O ₃).	1¾	Sides rough, test ends corroded off, absorbed melt.
Aluminous (approximately 60 percent Al ₂ O ₃).	½ to 1¾	Do.
Aluminous (approximately 90 percent Al ₂ O ₃).		Pulled apart above flux line after 4 hours.
Super duty fireclay.	½ to 1¾	Sides rough, all specimens expanded, test ends corroded off of 2, the others absorbed some slag.
Fused cast (approximately 50 percent MgO).	1¾	Sides smooth, test end corroded off.
High duty fireclay.	1 to 1¾	Sides smooth, all specimens were bloated and test ends were corroded off.
Zircon—silicon carbide.	1¾	Sides rough, test ends corroded off.
Chrome.		All specimens deformed, cracked, absorbed melt, and ends dropped off, 1 after 3½ hours and the other after 6½ hours of test.

¹ Chemical analysis: SiO₂, 19.1 percent; CaO, 42.5 percent; P₂O₅, 30.3 percent; Al₂O₃, 4.1 percent; Fe₂O₃, 3.8 percent; F, 0.66 percent; and MgO, trace.² Furnace with some rock phosphate heated to 575° to 750° F. in 8 hours, and the temperature was raised to 2,000° to 2,200° F. in the next 8 hours. Remainder of phosphate was charged and furnace heated to 2,825° F. in 2 hours. Furnace held at this temperature for 8 hours.³ The brick are arranged in the order of depth of penetration except when the test bricks absorbed slag, expanded, or cracked to such an extent that they would be unsatisfactory for use in refractory structures.⁴ U. S. Patent 2,231,944, Feb. 18, 1941.⁵ Test bricks were fabricated in the laboratory by the dry press process. They were pressed at 370 to 470 pounds per square inch and fired to 1,500° C.⁶ U. S. Patent 2,231,024, Feb. 11, 1941.⁷ U. S. Patent 2,231,945, Feb. 18, 1941.

for 2 hours, and then allowed to cool in the furnace for 18 hours before being removed for examination. To facilitate examination, the specimens were cut vertically through the center of the reacted zone with a silicon carbide saw. The depths of corrosion and of penetration were measured on the cut specimens. Depth of corrosion was taken as the distance from the original top surface to the bottom of the cavity caused by corrosion (C in fig. 12); depth of penetration was taken as the distance from the original top surface to the discernible limit of penetration of the fluid materials into the test brick (P in fig. 12). The electric furnace used in these tests had a firing

TABLE XX.—Results of tests in basic open-hearth molten slag ¹[Maximum temperature, 2,825° F.] ²

Material tested—brick	Maximum penetration (inches) ³	Remarks
Fused cast (approximately 70 percent Al_2O_3). Magnesia-Chrome	$\frac{3}{32}$ to $\frac{1}{16}$	Sides smooth, absorbed small amount of slag. Sides rough, absorbed slag, expanded above flux line, tended to pull.
Fused cast (approximately 90 percent Al_2O_3). Calcium oxide—chromium oxide ^{4,5}	$\frac{1}{16}$ to $\frac{1}{8}$	Sides smooth, no slag absorbed.
Calcium oxide—chromium oxide—zirconium oxide ^{6,7} Chrome	Not measurable	Sides smooth, absorbed slag, 1 brick cracked on cooling 30 days after testing, the other had swelled and cracked.
Calcium oxide—chromium oxide—zirconium oxide ^{6,7} Chrome	$\frac{1}{16}$ to $\frac{1}{8}$	Sides rough, absorbed slag, bloated slightly above flux line.
Super duty fireclay Chrome-Magnesia	$\frac{3}{16}$ to $\frac{1}{8}$	Sides rough, 1 specimen absorbed slag, expanded, cracked, and elongated above flux line and broke off during cooling, 2 other specimens cut off at the flux line 30 minutes after start of test and spalled, cracked, and elongated above flux line.
Forsterite-Chrome		Faces rough, corroded off at flux line.
Aluminous (approximately 60 percent Al_2O_3). Aluminous (approximately 90 percent Al_2O_3). Forsterite		Faces rough, corroded off at flux line, pulled off above flux line during tap, softened. Faces rough, corroded off at flux line 30 minutes after test started, softened, cracked, and elongated.
Magnesite Calcium oxide—zirconium oxide ^{6,7}		Faces rough, corroded off at flux line, 1 brick cracked off above flux line after 90 minutes of test. Faces rough, corroded off at flux line.
		Faces rough, corroded off at flux line 30 minutes after test started, softened, cracked, and elongated above flux line.
		All specimens spalled, 1 before test started. Test end of brick cracked off and dissolved in slag.

¹ Chemical analysis: Fe_2O_3 , 11.6 percent; CaO , 39.3 percent; SiO_2 , 19.1 percent; Fe_2O_3 , 18.1 percent; Al_2O_3 , 2.4 percent; Cr_2O_3 , 1.4 percent; MnO , 2.8 percent; MgO , 5.2 percent; and F , 0.1 percent.² Furnace with some slag heated to 2,000° to 2,200° F. in 16 hours. Remainder of slag charged and furnace heated to 2,825° F. in 2 hours. Furnace held at this temperature for 2 hours.³ The brick are arranged in the order of depth of penetration except when the test bricks absorbed slag, expanded, or cracked to such an extent that they would be unsatisfactory for use in refractory structures.⁴ Test bricks were fabricated in the laboratory by the dry-press process. They were pressed at 370 to 470 pounds per square inch and fired to 1,500° C.⁵ U. S. Patent 2,231,024, Feb. 11, 1941.⁶ U. S. Patent 2,231,944, Feb. 18, 1941.⁷ U. S. Patent 2,231,945, Feb. 18, 1941.

chamber approximately 12 inches wide by 20 inches deep by 16 inches high and was heated by means of six water-cooled Globar elements, each rated at 90 volts and 78.5 amperes, which were 24 inches long by 1 inch in diameter. A platinum—platinum-10 percent rhodium thermocouple in a porcelain protection tube was located centrally in the back of the firing chamber.

Results.—Results of tests of the resistance of refractory materials to lime are shown in table XXI and figure 13. Figure 13 shows the test bricks cut vertically through the centers of the areas attacked. The aluminous brick (60 and 70 percent Al_2O_3) were not damaged by the phosphate pellets, and the photograph shows these pellets moved back from their original position. With the other brick, the lime pellets were fluxed.

TABLE XXI.—Results of tests of refractories against pellets of lime ¹[Maximum temperature, 2,650° F.]²

Material tested—brick	Depth of corrosion, C (inches)	Depth of penetration, P (inches)	Arbitrary index of merit $\frac{1}{C \times P}$, in. ⁻²
Aluminous (approximately 70 percent Al_2O_3)	0	0	∞
Aluminous (approximately 60 percent Al_2O_3)	0	0	∞
Super duty fireclay	0	$\frac{3}{8}$ to $\frac{9}{16}$	∞
High duty fireclay	0	$\frac{3}{16}$ to $\frac{1}{4}$	∞
Low duty fireclay	$\frac{1}{16}$	$\frac{1}{16}$	0.5

¹ Chemical analysis: CaO, 96.45 percent; MgO, 1.7 percent; SiO₂, 1.5 percent; Fe₂O₃, 0.2 percent; S, 0.05 percent; P₂O₅, 0.02 percent; F, 0.08 percent.² Furnace and specimens heated to 2,650° F. in 21 to 22 hours and held at that temperature for 2 hours.

Table XXII shows the results of tests with Florida pebble phosphate and Tennessee brown rock phosphate as corrosives. Some of the exposed test specimens are shown in figures 14, 15, and 16. Before taking the photographs, the glassy products of reaction were removed from the top of the brick. No pellets are shown; where the depth of corrosion was great, the pellets were fused partially or completely.

In evaluating the test brick, an arbitrary index of merit was used. This index was taken as the reciprocal of the product of the depth of corrosion and the depth of penetration. It was devised as a single standard by which the refractories could be compared, though its applicability has not been established by service tests. Again, this method of evaluation is somewhat different from that used in another article (7) describing some of this work. The change in evaluation procedure was made to provide a single standard for comparison.

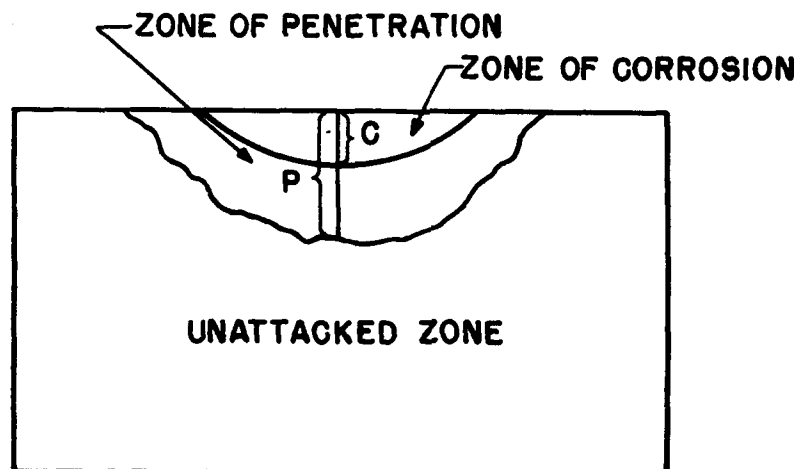


Figure 12.—Diagram of test brick after exposure to pellet of corrosive.

TABLE XXII.—Results of tests of refractories against pellets of phosphate

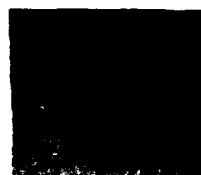
Material tested—brick	Florida phosphate ¹ at 2,650° F. ²				Florida phosphate ¹ at 2,825° F. ²				Tennessee phosphate ³ at 2,650° F. ²			
	Depth of corrosion, C (inches)	Depth of penetration, P (inches)	Arbitrary index of merit, $\frac{1}{C \times P}$ in. ⁻²		Depth of corrosion, C (inches)	Depth of penetration, P (inches)	Arbitrary index of merit, $\frac{1}{C \times P}$ in. ⁻²		Depth of corrosion, C (inches)	Depth of penetration, P (inches)	Arbitrary index of merit, $\frac{1}{C \times P}$ in. ⁻²	
Silica	0	0	∞		3/16	1 1/2	4		0	1 1/2	∞	
Super duty fireclay coated with high-temperature, air-setting chrome mortar	0	0	∞		5/16	2 3/8	1.5		3/8	3 1/4	11	
Super duty fireclay coated with high-temperature, air-setting chrome mortar ⁴									3/16	2 1/4	2.4	
Chrome-Magnesia	0	3/32	∞		1/16	1 1/8	21		3/32	3 1/4	20	
Aluminous (approximately 70 percent Al ₂ O ₃)	0	1/16	∞		3/4	1 7/8	2.1		5/8	5 1/4	11	
Aluminous (approximately 50 percent Al ₂ O ₃)	3/16	3/16	250		3/8	2 3/8	1.2		3/4	3 1/4	11	
Super duty fireclay	3/16 to 3/8	3/16 to 3/8	28 to 64		5/16	1 1/2 to 1 3/4	1.0 to 2.1		3/8 to 1/2	3 1/2 to 3 3/4	6 to 13	
Low duty fireclay	3/16	3/16	28		2 1/2	2 1/2	0.16		3/8 to 1/2	3 1/2 to 3 3/4	4 to 64	
Intermediate duty fireclay	3/4	3/4	16		1 1/2	1 1/2	1.9		3/8 to 1/2	3 1/2 to 3 3/4	8 to 110	
High duty fireclay	3/4	3/4	16		3/4	3/4	16		5/8 to 3/4	3 1/2 to 3 3/4	10 to 64	
Silicon carbide									0	3/8	30	
Chrome									1/16	3/16	26	
Zirconia									1/16	2 1/2	6	
Magnesite									3/4	5 1/4	20	
Super duty fireclay coated with high-temperature, air-setting fireclay mortar									1/16	13/16	20	
Caroline (50 percent) and silica (crushed) (50 percent) (monolithic)									3/16	1	16	
Caroline (60 percent) and silica (crushed) (40 percent) (monolithic)									3/8	9/16	14	
Caroline (50 percent) and firebrick grog (50 percent) (monolithic)									5/16	1 1/4	3	
Plastic firebrick (monolithic)									7/16	1 1/4	3	
Grog, super duty fireclay (67 percent) and high-temperature, air-setting fireclay mortar (33 percent) (monolithic)									1 1/2	1 1/2	1	
Grog, super duty fireclay (80 percent) and high-temperature, air-setting fireclay mortar (20 percent) (monolithic)									3/2	1 1/2	1	
Grog, super duty fireclay (77 percent) and Lumnite cement (9 percent) (monolithic)									3/2	1 1/2	1	
Silica (crushed) (50 percent) and bentonite (20 percent) (monolithic)									3/4	1 1/4	4	

¹ Chemical analysis: CaO, 45.2 percent; P₂O₅, 30.7 percent; SiO₂, 8.1 percent; F, 3.8 percent; CO₂, 3.7 percent; Fe₂O₃, 1.7 percent; Al₂O₃, 1.2 percent; and MgO, 0.6 percent.

² Furnace and specimens heated to test temperature in 21 to 22 hours and held at that temperature for 2 hours.

³ Chemical analysis: CaO, 40 percent; P₂O₅, 28.5 percent; SiO₂, 16.5 percent; F, 3 percent; Fe₂O₃, 3.2 percent; Al₂O₃, 3.9 percent; MgO, 0.6 percent; ignition loss, 5 percent.

⁴ Brick, super duty fireclay coated with chrome mortar tested against Tennessee phosphate at 2,825° F.



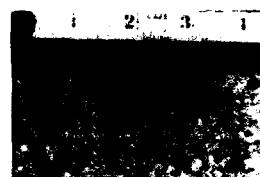
ALUMINOUS
(APPROX. 70% Al_2O_3)



ALUMINOUS
(APPROX. 60% Al_2O_3)



SUPER DUTY FIRECLAY



HIGH DUTY FIRECLAY



LOW DUTY FIRECLAY

Figure 13.—Sectional view of bricks after exposure to pellets of lime.



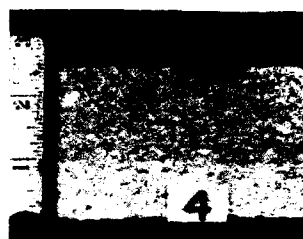
SILICA



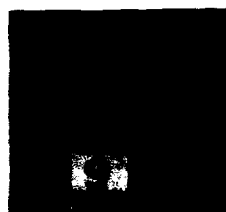
**SUPER DUTY FIRECLAY,
COATED WITH HIGH-
TEMPERATURE CHROME
MORTAR**



CHROME-MAGNESIA



**ALUMINOUS
(APPROX. 50% Al_2O_3)**



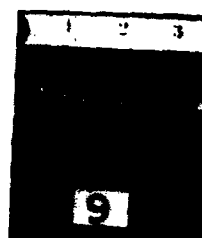
HIGH DUTY FIRECLAY

Figure 14.—Sectional view of bricks after exposure to pellets of Florida phosphate at 1,450° C. (2,642° F.).

Products of reaction were removed from the zone of corrosion.



CHROME-MAGNESIA



HIGH DUTY FIRECLAY



SILICA



**SUPER DUTY FIRECLAY,
COATED WITH HIGH-
TEMPERATURE CHROME
MORTAR**



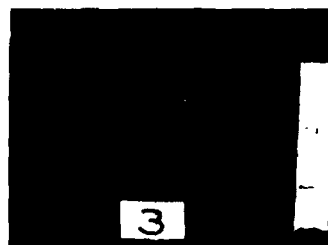
**ALUMINOUS
(APPROX. 50% Al_2O_3)**

Figure 15.—Sectional view of bricks after exposure to pellets of Florida phosphate at 1,550° C. (2,822° F.).

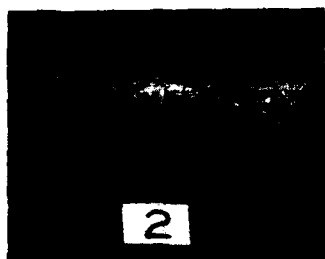
Products of reaction were removed from the zone of corrosion.



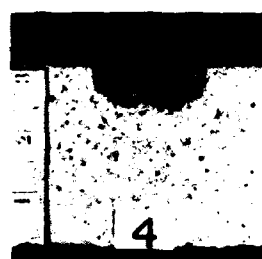
SILICA



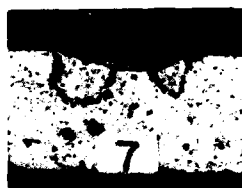
CHROME



CHROME - MAGNESIA



ALUMINOUS
(APPROX. 70% Al_2O_3)



SUPER DUTY FIRECLAY,
COATED WITH HIGH-TEMPERATURE
AIR-SETTING MORTAR

Figure 16.—Sectional view of bricks after exposure to pellets of Tennessee phosphate at 1,450° C. (2,642° F.).

Products of reaction were removed from the zone of corrosion.

Tests of Ceramic Materials in Strong Phosphoric Acid

Equipment and procedure.—Tests of the resistance of brick and ceramic tower packing materials to strong phosphoric acid (117 percent H_3PO_4) were carried out in the ceramic-lined tank (fig. 3) described under "Tests of Metals." Before exposing the specimens to the corrosive, they were dried and coated with a thin, impervious coating of paraffin, after which their volumes were determined by water displacement through use of an overflow volumeter. Volume determinations also were made after completion of the tests. The strong acid used in the tests was made by concentrating plant phosphoric acid and then fortifying it with phosphorus pentoxide. The acid temperature was maintained in the range 480° to 490° F. Specimen brick were held by stainless steel clamps on the rotating shafts so that half of their length was immersed in the acid. Packing rings were suspended from the shafts so that they were completely immersed in the acid.

The tests were of 21 days' duration. For the first 16 days the specimens were rotated in the acid continuously. During each of the last 5 days the specimens were raised out of the acid for 1 hour, immersed and allowed to rotate for $2\frac{1}{2}$ hours, raised out of the acid for 1 hour, immersed and allowed to rotate for $2\frac{1}{2}$ hours, raised a third time for 1 hour, and immersed and rotated for 16 hours. At the end of the 21 days the specimens were allowed to drain and cool over the bath, after which they were immersed in water for 96 hours to remove some of the acid that had been absorbed, drained again, dried, and coated with paraffin for volume determination. The purpose of raising and lowering the specimens was to determine whether they would be affected by the thermal shock incurred by this treatment.

Most of the specimens were rotated at 14 revolutions per minute, but some were turned at 30 revolutions per minute to determine whether the increased rate of rotation would have a marked effect on the rate of corrosion. In some of the tests movement of the specimens was the only means of agitation, but in others a Lightnin mixer was used to provide additional agitation. In neither case was the velocity of the acid at the surface of the ceramic specimens determined.

Results.—The results of the tests are given in table XXIII. Specimens were evaluated on the basis of volume loss except when they spalled or cracked. The materials that failed in these ways were considered unsuitable for service under the conditions of the test.

Table XXIII.—Results of tests in strong phosphoric acid¹

Material tested—brick	Volume loss, ² (percent)			Remarks
	Specimens rotated at 14 r. p. m., low-bath agitation rate	Specimens rotated at 30 r. p. m., low-bath agitation rate	Specimens rotated at 14 r. p. m., high-bath agitation rate	
Graphite.....	+1.0		+1.0	No visible attack, increased in size during test.
Carbon.....			.3	No visible attack.
Red shale, Ragland, Ala.....	1.3	0		Do.
Red shale, Ragland, Ala.....			1.8	Surface rough and pitted, original skin removed by acid.
Red shale, Daisy, Tenn.....			1.8	Brick cracked, surface rough and pitted, acid removed original skin.
Zircon.....	1.3			No visible attack.
High duty fireclay.....	1.4			Slight attack.
Super duty fireclay.....	.2			Slight attack, swelled slightly, started to crack.
Acid-resistant fireclay, Bessemer, Ala.....	2.3	4.2		Surface rough, acid removed original skin.
Aluminous (approximately 85 percent Al ₂ O ₃).....	1.4			Slight attack, but a thin layer was starting to come off, cracked after exposure on being leached to remove acid.
Silica.....				Shattered on being raised out of bath, final volume could not be determined.
Aluminous (approximately 60 percent Al ₂ O ₃).....				Shattered on being raised and lowered into the hot acid, final volume could not be determined.
Soapstone.....	.2			Badly attacked, acid leached out iron oxide forming fissures.
<i>Packing material</i>				
Carbon.....			0	No visible attack.
Red shale, Ragland, Ala.....			2.8	Rough surface after test.
Red shale, Daisy, Tenn.....			8.0	Volume losses high as ring spalled sometime during testing period, rough surface after test.
Zircon porcelain.....		5.0		Surface smooth.
Do.....			2.2	Ring cracked and spalled very slightly sometime during testing period, surface smooth.
Chemical porcelain.....	5.5		1.7	Surface rough.
Chemical stoneware.....	11.0		4.1	Do.
Pyrex glass.....	49.2			Surface smooth.

¹ Acid concentration, approximately 117 percent H₃PO₄; acid temperature, 480° to 490° F.² A "+" means an increase in volume.

Tests of Acid-Resistant Ceramic Materials in Boiling Phosphoric and Nitric Acids

Equipment and procedure.—Pieces of brick were tested for resistance to boiling phosphoric and nitric acids by a modification of a procedure outlined by Fairlie (1). The test materials were equiaxial pieces, minus 2 plus 3 mesh (Tyler sieve numbers, 0.437- and 0.263-inch openings), that were obtained by crushing and screening the brick to be tested.

After being washed and then dried at 212° F., 50-gram samples of the sized materials were placed in 1,000-milliliter flasks with 250 milliliters of 58° B. C. P. phosphoric acid (80 percent H₃PO₄) or 35° B. C. P. nitric acid (50 percent HNO₃). The flasks were provided with water-cooled reflux condensers fitted with ground-glass joints. The acids in the flasks were boiled continuously for 48 hours, and at

the end of this time the solids were allowed to settle. The clear acid was removed by decantation and that remaining with the solids was removed by washing in boiling water and removing the clear water extract by decantation. The water extraction was repeated until the pH of the decanted washings was approximately 7. The solids were predried at 212° F. and then dried to constant weight at 480° F. The loss in weight of the solids was determined. Absorption was determined on specimens according to the test procedure outlined by A. S. T. M. Designation C67.

Results.—In the selection of brick for general use in the TVA plant, the brick tested were evaluated on the basis of weight loss in boiling phosphoric acid, which was considerably greater than the weight loss of the same materials in boiling nitric acid. The results of tests in both acids are shown in table XXIV, together with absorption test data. Brick showing less than 4 percent weight loss in phosphoric acid were considered acceptable for use in the TVA plant. This criterion has proved to be satisfactory. Weight losses of red shale brick in both acids are roughly correlative with absorption; the losses increase as absorption increases. Therefore, absorption is a reasonably good measure of the quality of these brick for use in contact with acids. The data on the fireclay acid-resistant brick are not sufficient to permit correlation.

TABLE XXIV.—Results of tests of ceramic materials in boiling phosphoric acid and in boiling nitric acid

Material tested—brick	Weight loss in H_3PO_4 ¹ (percent)	Weight loss in HNO_3 ² (percent)	Absorption (percent)
Red shale, Ragland, Ala.	2.4		1.5
	2.9	0.37	.5
	5.6		5.3
Red shale, Canton, Ohio	2.7	1.2	5.3
	3.0	1.02	3.9
	3.9	2.1	5.1
Red shale, Ensley, Ala.	2.6	.34	2.3
	5.6	.81	4.6
	6.2		5.8
	7.7	1.8	7.8
Red shale, Plainville, Ga.	4.8		8.5
Red shale, Chattanooga, Tenn.	8.0		6.3
Acid-resistant fireclay, Beech Creek, Pa.	2.9	.33	4.7
	3.7	.33	4.1
Acid-resistant fireclay, Bessemer, Ala.	1.7	.3	3.6
	1.9	.93	4.8

¹ C. P., 80 percent phosphoric acid (b. p., 293° F.).

² C. P., 50 percent nitric acid (b. p., 241° F.).

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- (4) Miller, A. M., and Junkins, J. N., Chem. and Met. Eng. 50, 119-25 (1943).
- (5) Pole, G. R., and Beinlich, A. W., Bull. Am. Ceram. Soc. 20, 229-37 (1941).
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- (8) Thompson, H. L., Miller, Philip, McCamy, I. W., Johnson, R. M., and Hoffmeister, George, Jr., Ind. Eng. Chem. 42, 2176-82 (1950).
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Index A

Index of TVA Technical Articles Relating to Corrosion of Metals and Ceramics

"Corrosion of Metals in the Manufacture of Phosphoric Acid by Electric Furnace Process," Charles E. Hartford and R. L. Copson. *Ind. Eng. Chem.* 31, 1123-28. September 1939.

"Laboratory Corrosion Tests of Rotary Lime Kiln Refractories," G. R. Pole and A. W. Beinlich. *J. Am. Ceram. Soc.* 28, 357-60. December 1, 1945.

"New Refractory Compositions Resistant to Molten Rock Phosphate," G. R. Pole and A. W. Beinlich. *J. Am. Ceram. Soc.* 26, 21-37. January 1943.

"Nomograph for Calculation of Corrosion Rates," L. D. Yates and E. P. Tait. *Metal Progress* 42, 1059. December 1942.

"Testing Refractories Against the Corrosive Action of Electric Furnace Phosphate Slags," G. R. Pole and D. G. Moore. *J. Am. Ceram. Soc.* 19, 259-70. October 1936.

"Testing Refractories Against Molten Calcium Metaphosphate," G. R. Pole and A. W. Beinlich. *Bull. Am. Ceram. Soc.* 20, 229-37. July 1941.

Index B—Metals

Index of materials, compositions, and tables

Material tested	Approximate chemical composition of material (percent)	Tables in which results of tests of material appear
Admiralty	0.06 maximum Fe, 0.07 maximum Pb, 0.9 minimum Sn, 70 minimum Cu, balance Zn	I, V, VI.
Advance	54-55 Cu, 44-46 Ni	V, VI, X.
A. I. S. I. Type 302 stainless steel.	0.08-0.20 C, 2.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 17-19 Cr, 8-10 Ni.	V, VI, XI, XV.
A. I. S. I. Type 302+Mo welding rod.		IV, V, VI.
A. I. S. I. Type 303 stainless steel.	0.15 maximum C, 2.00 maximum Mn, 1.00 maximum Si, 0.07 minimum P, S, or Se, 17-19 Cr, 8-10 Ni, 0.06 maximum Mo or Zr.	V, VI, XVI.
A. I. S. I. Type 304 stainless steel.	0.08 maximum C, 2.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 18-20 Cr, 8-11 Ni.	I, V, VI, VII, X, XI, XII, XIII, XV, XVI.
A. I. S. I. Type 309 stainless steel.	0.20 maximum C, 2.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 22-24 Cr, 12-15 Ni.	I, IV, V, VI, XII.
A. I. S. I. Type 309 stainless steel welding rod.		XII.
A. I. S. I. Type 310 stainless steel.	0.25 maximum C, 2.00 maximum Mn, 1.50 maximum Si, 0.04 maximum S, 24-26 Cr, 19-22 Ni.	IV.
A. I. S. I. Type 316 stainless steel.	0.10 maximum C, 2.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 16-18 Cr, 10-14 Ni, 2.00-3.00 Mo.	I, II, III, IV, V, VI, VII, IX, X, XI, XII, XIV, XV.
A. I. S. I. Type 316+Cb stainless steel.	0.10 maximum C, 2.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 16-18 Cr, 10-14 maximum Ni, 2.00-3.00 Mo (10 x C) Cb.	I.
A. I. S. I. Type 316 stainless steel welding rod.		V, VI, IX, XII.
A. I. S. I. Type 316+Cb stainless steel welding rod.		V, VI, XII.
A. I. S. I. Type 317 stainless steel.	0.10 maximum C, 2.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 18-20 Cr, 11-14 Ni, 3-4 Mo.	IV, VI.
A. I. S. I. Type 320 stainless steel.	0.12 maximum C, 0.7 Mn, 0.75 Si, 17 minimum Cr, 7 minimum Ni (5.5 x C) minimum Ti, balance Fe.	V, VI.
A. I. S. I. Type 321 stainless steel.	0.08 maximum C, 2.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 17-19 Cr, 9-11 Ni (5 x C) minimum Ti.	V.
A. I. S. I. Type 329 stainless steel.	0.10 maximum C, 25-30 Cr, 3-5 Ni, 1-1.5 Mo.	I, V, VI, VII, XVI.
A. I. S. I. Type 347 stainless steel.	0.08 maximum C, 2.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 17-19 Cr, 9-12 Ni (10 x C) minimum Cb.	I, IV, V, XII.
A. I. S. I. Type 347+Cb welding rod.		XII.
A. I. S. I. Type 405 stainless steel.	0.08 maximum C, 1.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 11.5-13.5 Cr, 0.10-0.30 Al.	XIII.
A. I. S. I. Type 410 stainless steel.	0.15 maximum C, 1.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 11.5-13.5 Cr.	I, II, XIII, XV, XVI.
A. I. S. I. Type 416 stainless steel.	0.15 maximum C, 1.25 maximum Mn, 1.00 maximum Si, 0.07 minimum P, S, or Se, 12-14 Cr, 0.80 maximum Mo or Zr.	II, XIII.
A. I. S. I. Type 430 stainless steel.	0.12 maximum C, 1.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 14-18 Cr.	I, II, V, VI, VII, VIII, X, XII, XIII, XV, XVI.
A. I. S. I. Type 430 stainless steel welding rod.		XII, XIII.
A. I. S. I. Type 446 stainless steel.	0.35 maximum C, 1.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 23-27 Cr, 0.25 maximum N (over) 0.10 C, 1.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 4-6 Cr.	I, IV, V, VI, VII, XII, XVI.
A. I. S. I. Type 501 stainless steel.		I, II, VIII, XII, XIII, XIV.
A. I. S. I. Type 502 stainless steel.	0.10 maximum C, 1.00 maximum Mn, 1.00 maximum Si, 0.04 maximum P, 0.03 maximum S, 4-6 Cr.	I, X, XIII, XIV.
Allegheny 55 (cast).	0.35 maximum C, 1 maximum Mn, 23-30 Cr, 0.6 maximum Ni, 0.6 maximum Si, balance Fe.	V, VI.

Index B—Metals—Continued

Index of materials, composition, and tables—Continued

Material tested	Approximate chemical composition of material (percent)	Tables in which results of tests of material appear
Aluminum	99+ Al	I, XII, XIII, XV.
Aluminum welding rod		XII, XIII.
Albrac A	20 Ni, 5 Zn, 75 Cu	XI.
AMSCOF-3 (cast)	26-29 Cr, 0.3 Ni, balance Fe	V, VI.
Anti-oxid metal (cast)	75 Cu, 10 Sn, 15 Pb	V, VI.
A. S. T. M. Designation: A198-39, grade A (cast).	0.07 maximum C, 1.00 maximum Mn, 2.00 maximum Si, 0.05 maximum P, 0.05 maximum S, 18 minimum Cr, 8 minimum Ni	XII.
A. S. T. M. Designation: A296-46T, grade 8.	0.20 maximum C, 2.00 maximum Mn, 2.00 maximum Si, 0.05 maximum P, 0.05 maximum S, 23-27 Cr, 19-22 Ni	XII.
Beryllium copper	2.5-3.0 Be, balance Cu	V, VI.
Brass, high	65 Cu, 35 Zn or (69-43 Cu, 2.25-3.25 Pb, 0.15 Fe, balance Zn)	I, V, VI.
Brass, red	85 Cu, 15 Zn	I, II, III, IV, V, VI, VII, IX, X, XI, XV, XVI.
Brass, yellow	60-70 Cu, 27-40 Zn, 5.3 Pb, 0-1 Sn	XIII, XV, XVI.
Bronze, aluminum	95 Cu, 5 Al	IV, V, VI.
Bronze, commercial (cast)	90 Cu, 10 Zn	V, VI.
Bronze, leaded	62-88 Cu, 10-35 Zn, 1.7-2.6 Pb	XV.
Bronze, manganese (cast)	59 Cu, 39 Zn, 1.2 Fe, 0.7 Sn, 0.05 Mn	V, VI.
Bronze, nickel-aluminum (cast)	92 Cu, 4 Al, 4 Ni	V, VI.
Bronze, Phosphor	94.5 Cu, 5.4 Sn, 0.01 P	IV.
Bronze, Phosphor C	92 Cu, 8 Sn	I, V, VI, X.
Bronze, Phosphor D	89.5 Cu, 10.5 Sn	I, V, VI, XI, XV.
Bronze, silicon	95-97 Cu, 3-5 Si	VI.
Bronze, Superstrength (cast)	63 Cu, 27 Zn, 6 Al, 3 Fe, 1 Mn	V, VI.
Bronze, Tobin	60.1 Cu, 39.1 Zn, 0.7 Sn	V, VI, X, XI.
Carpenter 20	20 Cr, 29 Ni, 1.75 Mo, 3.5 Cu, 1.0 Si, 0.07 C	V, VI, X.
Cast iron, gray (cast)	3.25 C, 0.07 S, 2.0 Mn, 2.2 Si, balance Fe	V, VI, VIII, XIII, XIV, XV, XVI.
Cast iron (malleable)		V.
Chlorimet 2 (cast)	0.10 C, 63 Ni, 1.0 Si, 32 Mo, 3.0 Fe	I, IV.
Circle L-34 (cast)	0.07 C, 19 Cr, 29 Ni, 2.25 Mo, 1.2 Si, 0.02 Al, 0.37 Cu	I, IV, V, VI, X, XI.
Coast metal 4 (cast)	4.0 C, 16 Cr, 6 Ni, 4.5 Si	IV.
Coast metal 10 (cast)	4.0-4.25 C, 16 Cr, 2 Ni, 8 Mo	IV.
Coast metal 12 (cast)	4.25 C, 16 Cr, 6 Ni, 8 Mo, 1 Ti	IV.
Coast metal 18 (cast)	2.25-2.75 C, 25 Cr, 15 Ni, 8 Mo, 25 Co	IV.
Copper	99.9 Cu	V, VI, XV.
Copper, deoxidized	99.95 Cu, 0.01-0.05 P	I, V, VI, X, XI, XV.
Croloy 9	0.15 maximum C, 0.50 maximum Mn, 1.25-1.75 Mo, 8-10 Cr, balance Fe	V, VI.
Croloy 25-20	0.15 C, 1.0 Mn, 0.75 Si, 25 Cr, 20 Ni, balance Fe	V, VI.
Cupro-Nickel 20 percent	75 Cu, 20 Ni, 5 Zn	V, VI.
Duraloy A	0.25 C, 27-30 Cr, 0.60 Mn, balance Fe	V, VI.
Durichlor (cast)	14.5 Si, 3.0 Mo, 0.85 C, 0.65 Mn, balance Fe	V, VI, VII, X, XI.
Durimet	0.08 C, 18-46 Cr, 21.7 Ni, 2.3 Mo, 0.88 Si, 0.2 Cu	I, IV, VII, X, XI, XV.
Durimet 20 (cast)	20 Cr, 29 Ni, 1.75 Mo, 3.5 Cu, 1.0 Si, 0.07 C	I, XIII.
Durimet T	19 Cr, 22 Ni, 1 Si, 1 Cu, 3 Mo, 0.07 C	XIII.
Duriron (cast)	0.85 C, 14.5 Si, 0.65 Mn, balance Fe	I, IV, V, VI, X, XI.
Easy-Flu	50 Ag, 15.5 Cu, 16.5 Zn, 18 Cd	XV.
Elcomet K (cast)	0.12 C, 23 Cr, 22 Ni, 1 Si, 3-4 Cu, 2 Mo, 0.3 Mn, balance Fe	IV, X.
Enduro NC-3 (cast)	0.25 maximum C, 2.0 maximum Si, 1.5 maximum Mn, 24-26 Cr, 19-21 Ni	V, VI.
Everbrite (cast)	60 Cu, 30 Ni, 3 Fe, 3 Cr, 3 Si	V, VI, X.
Everdur 1010	95.8 Cu, 3.1 Si, 1.1 Mn	I, IV, V, VI, X, XI, XV, XVI.
Everdur 1010 welding rod		VI.
Everdur 1015	98 Cu, 1.25 Si, 0.25 Mn	I, V, VI.
Ferritic cast chromium steel (cast)	0.08 C, 16.4 Cr, 0.76 Ni	XII.
Gold	99+ Au	VI.
Hastelloy A (cast and wrought)	58 Ni, 20 Mo, 2 Mn, balance Fe	I, IV, V, VI, VII, XV.
Hastelloy A welding rod		V.
Hastelloy B (cast and wrought)	33 maximum Mo, 7 maximum Fe, balance Ni	I, IV, V, VI, VII, X.
Hastelloy B welding rod		IV, V.
Hastelloy C (cast)	20 maximum Mo, 18 maximum Cr, 6 maximum W, 7 maximum Fe, balance Ni	IV, V, VI.
Hastelloy D (cast)	85-90 Ni, 7 Cu, 10 Si, balance Fe	IV, V, VI, X.
Illum G (cast)	56 Ni, 24 Cu, 8 Cu, 4 Mo	I, V, VI.
Illum R	61 Ni, 21 Cr, 6.5 Mo, 6.5 Fe, 4 Cu, 0.76 Mn, 0.51 W	IV.

Index B—Metals—Continued

Index of materials, composition, and tables—Continued

Material tested	Approximate chemical composition of material (percent)	Tables in which results of tests of material appear
Inconel	11-15 Cr, 70 minimum Ni, 1.0 maximum Mn, 10 maximum Fe, 0.5 maximum Si, 0.15 maximum C	IV, V, VI, XV.
La Bour R-55 (cast)	23 Cr, 52 Ni, 4 Mo, 4 Si, 8 Fe, 6 Cu, 2 W, 0.2-0.3 C	I, IV.
La Bour G-60 (cast)	23-25 Cr, 63-65 Ni, 5-6 Cu, 2-4 Mo, 2-4 W, 0.8 Si, 1 Fe, 0.2 Mn, 0.06 C	I, IV.
Lead, chemical	99.9+ Pb	I, V, VI, X, XI, XIII, XV.
Lead, tellurium	0.06 Te, 0.06 Cu, balance Pb	I, V, VI, X, XI, XIII.
Low-chrome iron	4-6 Cr, 0.12 C	I, V.
Low-chrome iron+Cb	5 Cr, 4 Mo, 0.6 Cb, 0.06 C	I, V.
Manganese 18-8 stainless steel	18.6 Cr, 2.13 Ni, 0.13 Mn	I, IV.
Medium-chrome iron	0.12 C, 11-15 Cr	V.
Mild steel	0.21 C, 0.4 Mn, 0.2 Si, balance Fe	I, IV, V, VI, VIII, IX, X, XIII, XIV, XV, XVI.
Mild steel welding rod		V, IX, XIII.
Monel	68 Ni, 29 Cu, 2 Fe, 1.5 Mn, 0.25 C	I, IV, V, VI, VII, X, XI, XV, XVI.
Monel K	63 Ni, 30 Cu, 3.5 Al, 1.5 Fe, 0.2 C	I, V, VI, X, XI.
Monel S (cast)	64 Ni, 29 Cu, 2.5 Fe, 0.5 C	V, VI, X.
Monel welding rod No. 130-X		VI.
Muntz metal (cast)	60 Cu, 40 Zn	I, V, VI.
Nichrome V	80 Ni, 20 Cr	IV, V, VI.
Nickel	99.4 minimum Ni	IV, V, VI, XV.
Ni-Resist (cast)	12-15 Ni, 5-7 Cu, 2.75-3.1 C, 1.5-4 Cr, 1.25-2 Si, 1-1.5 Mn	V, VI.
Ni-Resist, copper free (cast)	15-20 Ni, 2.5 maximum Cr, 1-1.5 Mn, 0.6-2 Si, 2.2 C	V, VI.
Olympic A	96 Cu, 3 Si, 1 Zn	V, VI.
Olympic D	95.5 Cu, 3 Si, 0.5 P, 1 Zn	V, VI.
Phos-Copper welding rod		V, VI.
Pioneer metal (cast)	25 Cr, 35 Ni, 5 Mo, balance Fe	I, IV, V, VI, X.
Platinum	100 Pt	VI.
Resistac (cast)	88 Cu, 10 Al, 2 Fe	V, VI, X, XI.
Silerome 25-20	24-26 Cr, 19-20 Ni, 0.25 C	V, VI.
Sil-fos welding rod	15 Ag, 80 Cu, 5 P	V, VI.
Silver, fine	99.9 Ag	VI, XV.
Solder	60 Sn, 40 Pb	V, VI.
Sterling silver	92.5 Ag, 7.5 Cu	IV, VI, XV.
Super nickel	70 Cu, 30 Ni	V, VI, X, XI, XVI.
Tantalum	100 Ta	IV.
Worhtite (cast)	20 Cr, 24 Ni, 3.0 Mo, 0.07 maximum C	I, V, VI, XII.
Zorite	15 Cr, 35 Ni, 0.5 maximum C, balance Fe	V, VI, XI.

Index C—Ceramics

Index of materials, compositions, physical properties, and tables

Material tested—bricks or other shapes	Approximate chemical analysis (percent)	Apparent sp. gr., g./cc.	Bulk sp. gr., g./cc.	Absorption (percent)	Porosity (percent)	P. C. E. cone	Tables in which results of tests of materials appear
Acid-resistant fireclay, Beech Creek, Pa.	58.4 SiO ₂ , 2.2 TiO ₂ , 3.1 Fe ₂ O ₃ , 33.0 Al ₂ O ₃ , 3.8 CaO, 0.9 MgO, 2.6 alkalis.	2.50	2.24 to 2.26	4.1 to 4.7	9.3 to 10.7	31 to 32	XXIV.
Acid-resistant fireclay, Bessemer, Ala.	57.8-60.4 SiO ₂ , 1.5-1.8 TiO ₂ , 2.9-3.0 Fe ₂ O ₃ , 30.9-32.0 Al ₂ O ₃ , 0.7-3.8 CaO, 0.9 MgO, 0.3-0.4 alkalis.	2.51 to 2.54	2.26 to 2.30	3.6 to 4.7	8.3 to 10.8		XXIII, XXIV.
Aluminous (approximately 50 percent Al ₂ O ₃)	36.7-42.0 SiO ₂ , 1.2-3.1 TiO ₂ , 0.9-1.8 Fe ₂ O ₃ , 33.3-35.0 Al ₂ O ₃ , 0.5-1.0 CaO, 3.3-3.9 MgO.	2.95 to 3.06	2.14 to 2.23	12.2 to 12.9	27.2 to 27.6	34+	XVII, XIX, XXII.
Aluminous (approximately 60 percent Al ₂ O ₃)	24.5-37.2 SiO ₂ , 0.6-3.5 TiO ₂ , 0.7-3.8 Fe ₂ O ₃ , 56.8-66.9 Al ₂ O ₃ , 0.0-1.8 CaO, 0.0-1.6 MgO.	2.94 to 3.11	1.80 to 2.59	6.5 to 19.1	16.4 to 35.9	34+	XVII, XVIII, XIX, XX, XXI, XXIII.
Aluminous (approximately 70 percent Al ₂ O ₃)	22.9-30.0 SiO ₂ , 2.4-3.2 TiO ₂ , 0.8-3.6 Fe ₂ O ₃ , 63.8-73.3 Al ₂ O ₃ , 0.0-1.1 CaO, 0.0-0.2 MgO.	3.12 to 3.21	2.38 to 2.55	8.1 to 10.0	20.6 to 23.8	34+	XVII, XXI, XXII.
Aluminous (approximately 85 percent Al ₂ O ₃)	15.7 SiO ₂ , 0.1 TiO ₂ , 0.8 Fe ₂ O ₃ , 84.6 Al ₂ O ₃ , 0.0 CaO, 0.0 MgO.	3.67	2.55	12.0	30.0		XXIII.
Aluminous (approximately 90 percent Al ₂ O ₃)	10.1 SiO ₂ , 1.2 TiO ₂ , 1.1 Fe ₂ O ₃ , 86.1 Al ₂ O ₃ , 0.3 CaO, 0.0 MgO.	3.54 to 3.58	2.63 to 2.81	7.7 to 9.8	21.5 to 25.7	34+	XVII, XIX, XX.
Calcium oxide—chromium oxide	98.0 Cr ₂ O ₃ , 27.8 CaO	4.17 to 4.37	2.21 to 2.38	19.2 to 21.3	45.6 to 47.0	36+	XVII, XIX, XX.
Calcium oxide—chromium oxide—zirconium oxide	37.7 Cr ₂ O ₃ , 33.7 ZrO ₂ , 28.5 CaO	4.41 to 4.50	2.50 to 2.66	15.4 to 17.2	40.9 to 43.1	36+	XVII, XIX, XX.
Calcium oxide—zirconium oxide	76.5 ZrO ₂ , 21.3 CaO	4.80 to 4.85	2.43 to 2.95	13.3 to 20.3	39.2 to 49.3	36	XVII, XIX, XX.
Carbon	Chemical analysis not determined	2.05	1.50	17.7	26.6		XXIII.
Chemical porcelain	do	2.40	2.37	0.6	1.3		XXIII.
Chemical stoneware	do	3.66 to 3.91	2.33	0.6	1.4		XXIII.
Chrome	53-64 SiO ₂ , 0.6-0.8 TiO ₂ , 9.8-12.9 Fe ₂ O ₃ , 15.3-21.9 Al ₂ O ₃ , 25.6-29.2 Cr ₂ O ₃ , 2.0-2.6 CaO, 27.8-34.1 MgO, 0.0-5.1 ignition loss.	2.40	2.63 to 3.11	5.7 to 12.3	17.2 to 32.5	30+	XVII, XIX, XX, XXII.
Chrome-Magnesia	5.7 SiO ₂ , 10.8 Fe ₂ O ₃ , 21.4 Al ₂ O ₃ , 24.4 Cr ₂ O ₃ , 2.5 CaO, 35.8 MgO.	3.96	2.90	8.6	24.8	36+	XVII, XIX, XX, XXII.
Electrocast (approximately 75 percent Al ₂ O ₃)	17.5 SiO ₂ , 3.0 TiO ₂ , 1.0 Fe ₂ O ₃ , 77.6 Al ₂ O ₃ , 1.2 CaO, 0.3 MgO.	3.33	3.26	0.8	2.1	36+	XVII, XVIII, XIX.
Electrocast containing zircon	11.7 SiO ₂ , 1.4 Fe ₂ O ₃ , 39.6 Al ₂ O ₃ , 22.9 Cr ₂ O ₃ , 1.0 CaO, 3.4 MgO.	3.77	3.63	0.7	2.4	36+	XVIII, XIX.
Forsterite	32.8 SiO ₂ , 8.3 Fe ₂ O ₃ , 2.5 Al ₂ O ₃ , 2.9 CaO, 49.5 MgO.	3.36	2.36	12.5	29.6	35	XVII, XX.
Forsterite-Chrome	25.2 SiO ₂ , 9.9 Fe ₂ O ₃ , 1.0 Al ₂ O ₃ , 10.9 Cr ₂ O ₃ , 1.6 CaO, 51.9 MgO.	3.47	2.75	7.6	20.8	36+	XVII, XX.

Fused, cast (approximately 70 percent Al_2O_3)	27 SiO_2 , 1.6 TiO_2 , 4.6 FeO , 73.4 Al_2O_3 , 7.9 CaO , 0.6 CaO , 5.3 MgO	3.82 to 3.87	3.07 to 3.54	2.4 to 6.4	8.3 to 10.5	36+	XVII, XVIII, XIX, XX.
Fused, cast (approximately 90 percent Al_2O_3)	1.2 SiO_2 , 2.0 TiO_2 , 0.8 FeO , 93.0 Al_2O_3 , 4.0 MgO	3.66 to 3.77	3.52 to 3.50	1.1 to 1.3	3.9 to 4.7	36+	XVII, XVIII, XIX, XX.
Fused, cast (approximately 50 percent MgO)	1.9 SiO_2 , 0.6 TiO_2 , 0.8 FeO , 32.1 Al_2O_3 , 15.1 CaO , 49.3 MgO , 0.5 alkalies	3.34	2.63	8.1	21.3	34+	XVII, XVIII, XIX.
Glass refractory	60.9-67.6 SiO_2 , 1.8-2.1 TiO_2 , 0.5-1.7 FeO , 28.5-36.8 Al_2O_3 , 0.1-0.7 CaO , 0.2-0.5 MgO	2.58 to 2.63	2.08 to 2.18	7.2 to 9.3	15.9 to 19.4	30 to 33	XVIII.
Graphite	Chemical analysis not determined	2.07 to 2.10	1.33 to 1.53	17.6 to 26.9	27.0 to 35.8		XXIII.
High duty fireclay	51.5-61.3 SiO_2 , 1.5-2.3 TiO_2 , 1.6-2.7 FeO , 32.5-41.7 Al_2O_3 , 0.3-1.3 CaO , 0.1-1.6 MgO	2.58 to 2.68	1.97 to 2.42	3.9 to 11.9	9.4 to 23.5	30 to 33	XVIII, XIX, XXI, XXII, XXIII.
Intermediate duty fireclay	56.4-62.0 SiO_2 , 1.4-1.8 TiO_2 , 2.3-2.8 FeO , 31.3-36.4 Al_2O_3 , 0.3-2.4 CaO , 0.6-1.0 MgO , 0.0-0.28 alkalies	2.56 to 2.62	2.01 to 2.08	8.8 to 10.9	18.3 to 22.2	29 to 30	XXII.
Low duty fireclay	60.4-63.6 SiO_2 , 1.6-1.9 TiO_2 , 2.3-3.9 FeO , 28.0-34.9 Al_2O_3 , 0.5 CaO , 1.1-1.2 MgO	2.39 to 2.46	2.06 to 2.22	4.1 to 10.9	9.0 to 22.6	26	XVIII, XXI, XXII.
Magnesia-Chrome	7.5 SiO_2 , 6.1 FeO , 11.1 Al_2O_3 , 13.0 Cr_2O_3 , 5.8 CaO , 52.8 MgO	3.65	2.90	7.1	20.5	30+	XX.
Magnesite	27.5 SiO_2 , 0.0-5.9 FeO , 0.0-5.1 FeO , 0.4-12.3 Al_2O_3 , 0.0-10.0 Cr_2O_3 , 1.7-6.8 CaO , 52.7-57.3 MgO , 0.0-4.6 ignition loss	3.50 to 3.52	2.54 to 2.86	6.6 to 7.0	18.8 to 27.2	35+	XVII, XIX, XX, XXII.
Plastic firebrick	Chemical analysis not determined						
Pyrex glass	do	2.51 to 2.60	2.27 to 2.29	5.1 to 5.3	11.7 to 12.1		XXII.
Red shale, Canton, Ohio	66.7 SiO_2 , 1.1 TiO_2 , 7.8 FeO , 20.0 Al_2O_3 , 0.5 CaO , 0.8 MgO	2.53	2.28 to 2.32	6.3	13.7		XXIII.
Red shale, Chattanooga, Tenn.	63.3 SiO_2 , 1.1 TiO_2 , 9.3 FeO , 19.9 Al_2O_3 , 0.4 CaO , 3.0 MgO	2.53 to 2.58	2.21 to 2.42	3.7 to 4.5	8.6 to 10.5		XXIV.
Red shale, Ensley, Ala.	65.8 SiO_2 , 0.9 TiO_2 , 9.1 FeO , 21.7 Al_2O_3 , trace CaO , 1.5 MgO	2.53 to 2.67	2.21 to 2.42	2.3 to 7.8	5.4 to 17.2		XXIV.
Red shale, Plainville, Ga.	66.3 SiO_2 , 1.0 TiO_2 , 7.2 FeO , 16.7 Al_2O_3 , 0.21 CaO , 1.6 MgO			8.5			XXIV.
Red shale, Ragland, Ala.	37.0 SiO_2 , 11.5 FeO , 4.6 Al_2O_3 , 2.7 CaO , 28.5 MgO , 15.9 ignition loss	2.9	2.9	0.2	0.5	13	XXIII.
Soapstone	93.2-97.1 SiO_2 , 0.0-0.2 TiO_2 , 1.3-1.8 FeO , 0.2-0.7 Al_2O_3 , 0.4-3.2 CaO , 0.0-1.0 MgO	2.32	1.80	12.6	22.7	31 to 32	XVII, XIX, XXII, XXIII.
Silica	7.1 SiO_2 , 0.8 FeO , 3.4 Al_2O_3 , 1.7 CaO , 0.7 MgO	3.07	2.42		21.3		XXII.
Silicon carbide	51.8-56.5 SiO_2 , 1.0-3.3 TiO_2 , 0.2-2.1 FeO , 39.5-42.8 Al_2O_3 , 0.0-0.8 CaO , 0.0-0.3 MgO , 0.0-2.2 alkalies	2.67 to 2.71	2.26 to 2.39	4.7 to 6.8	11.0 to 15.3	33 to 34	XVII, XVIII, XIX, XX, XXI, XXII, XXIII.
Super duty fireclay	31.9-35.3 SiO_2 , trace-0.3 TiO_2 , 0.4-0.9 FeO , 3.1-5.2 Al_2O_3 , 58.1-62.9 ZrO_2 , 0.0-1.1 CaO , 0.0 MgO	4.32 to 4.53	3.30 to 3.58	4.8 to 8.3	17.2 to 27.3	38+	XVII, XVIII, XIX, XXII, XXIII.

See footnotes at end of table.

Index C—Ceramics—Continued *Index of materials, compositions, physical properties,¹ and tables—Continued*

Material tested—bricks or other shapes	Approximate chemical analysis (percent)	Apparent sp. gr., g./cc.	Bulk sp. gr., g./cc.	Absorption (percent)	Porosity (percent)	P. C. E. cone	Tables in which results of tests of materials appear
Zircon porcelain.	46.5 SiO ₂ , 16.2 Al ₂ O ₃ , 35.8 ZrO ₂ , 0.6 Fe ₂ O ₃ , 0.7 MgO, 0.0 CuO, 0.5 TiO ₂	3.14	3.13	0.2	0.5		XXIII.
Zircon—silicon carbide	24.2 SiO ₂ , 1.0 TiO ₂ , 1.4 Fe ₂ O ₃ , 2.9 Al ₂ O ₃ , 49.5 ZrO ₂ , 0.7 CaO, 0.0 MgO, 22.0 SiC.	3.80 to 4.08	2.82 to 3.24	5.6 to 9.2	21.4 to 25.8	36+	XVII, XVIII, XIX.
<i>Aggregates, binders, and mortars</i>							
Bentonite (binder)	Chemical analysis not determined.					31	XXII, XXIII.
Caroline (binder)	80.2 SiO ₂ , 0.6 TiO ₂ , 1.4 Fe ₂ O ₃ , 12.1 Al ₂ O ₃ , 0.0 CaO, 0.0 MgO, 4.8 ignition loss.						
Chrome, high-temperature, air-setting (mortar).	Chemical analysis not determined.						XXII.
Fireclay, high-temperature, air-setting (mortar).	55.8 SiO ₂ , 1.7 TiO ₂ , 1.3 Fe ₂ O ₃ , 31.4 Al ₂ O ₃ , 0.0 CaO, 1.3 MgO, 6.9 ignition loss.						XXII.
Lumnite cement (binder)	8.8 SiO ₂ , 2.7 TiO ₂ , 8.5 Fe ₂ O ₃ , 9.7 FeO, 35.4 Al ₂ O ₃ , 34.2 CaO, 2.8 MgO.						XXII.
Silica (crushed) (aggregate)	Chemical analysis not determined.						XXII.
Topaz (aggregate)	do						XXII.

¹ Physical properties determined by procedures outlined by A. S. T. M.

² U. S. Patent 2,231,924, Feb. 11, 1941.

³ U. S. Patent 2,231,944, Feb. 18, 1941.

⁴ U. S. Patent 2,231,945, Feb. 18, 1941.

⁵ Fe₂O₃ and FeO reported as FeO.

U. S. GOVERNMENT PRINTING OFFICE: 1951

For sale by the Superintendent of Documents, U. S. Government Printing Office
 Washington 25, D. C. Price 20 cents